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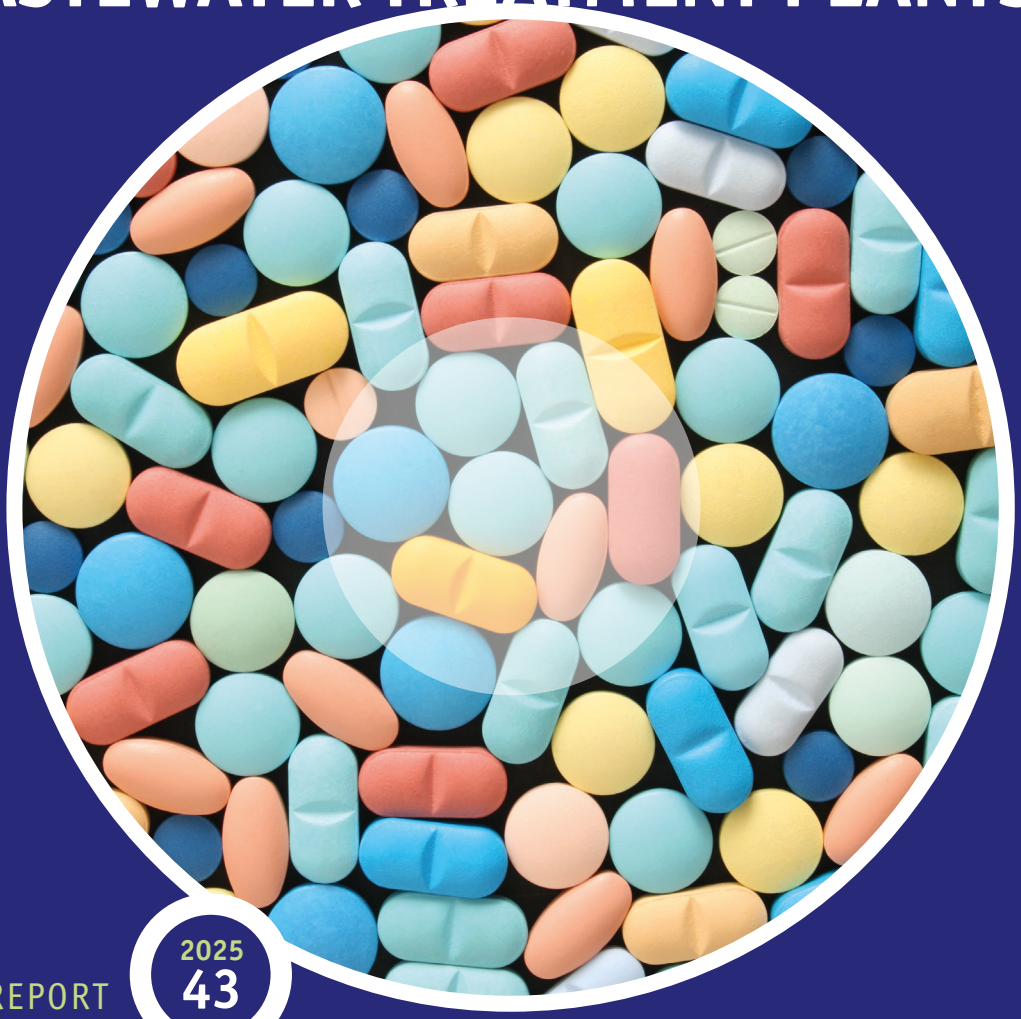
EVALUATION INNOVATION PROGRAMME REMOVAL OF MICROPOLLUTANTS AT WASTEWATER TREATMENT PLANTS



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The project executors of all IPMV pilot studies have been involved in this evaluation multiple times. Throughout the duration of the program, Mirabella Mulder was the coordinator of the IPMV program.

FOREWORD

INNOVATIVE TECHNOLOGIES FOR REMOVING MICROPOLLUTANTS AT WASTEWATER TREATMENT PLANTS (WWTPS) ARE NOW READY FOR FULL-SCALE IMPLEMENTATION.

The Innovation Programme Removal of Micropollutants at wastewater treatment plants (Dutch acronym: IPMV) has demonstrated that new technologies for removing micropollutants from WWTP effluent are both feasible and promising. Compared to reference methods – ozonation, powdered activated carbon in activated sludge (PACAS) and granular activated carbon filtration (GAC) – they can offer higher removal efficiencies, lower costs, and/or a reduced CO2 footprint.

During the past five years, the IPMV has investigated the feasibility of a large number of innovative technologies and, if promising, scaled these up to pilot study level. This report presents and compares the results of 15 such pilots. The evaluation demonstrates that the ozonation and PACAS reference technologies continue to be attractive from a cost perspective, but that new technologies offer advantages with regard to CO_2 footprint, removal efficiency and/or nutrient removal.

The IPMV is part of the Chain Approach to reduce pharmaceutical residues in water, a national effort initiated by the Dutch Ministry of Infrastructure and Water Management (Min. I&W). The IPMV ran for five years, from 2019 through 2023. Its goal was to pave the way for promising new technologies, improvements to existing technologies and/or innovative combinations of existing technologies. As such, it aimed to give water authorities access to a wider range of removal technologies, from which they could make their own selections, weighing the needs and constraints faced by their wastewater treatment plants (WWTPs). Nonetheless, while there are measures WWTPs can take to contribute to a range of water quality objectives, source control continues to be the preferred approach.

The IPMV's investigation of innovative removal technologies, or combinations of technologies, focused primarily on answering four questions:

- What annual average removal efficiencies can be achieved for selected indicator substances, and how do these correlate to the indicator substances stated in the revised EU Urban Wastewater Treatment Directive (entered into force on 1 Januari 2025)?
- To what extent do the innovative technologies reduce ecotoxicological risks from discharging wastewater into surface water, compared to the reduction by the three reference technologies (PACAS, GAC and ozonation)?
- What are the costs in proportion to the costs of the reference technologies?
- How does the sustainability of the innovative technologies compare to that of the reference technologies?

The programme concludes that the investigated innovative technologies do offer advantages compared to the reference technologies, in terms of removal efficiencies as well as costs and sustainability. One example is the development of biological activated carbon filtration (BACF), which significantly extends the service life of granular activated carbon while enabling biological degradation of micropollutants. Another example is the development of new adsorbents, such as cyclodextrins and high-silica zeolites, as alternatives to activated carbon. For several of the innovative technologies, outstanding research questions still need to be answered in follow-up pilot studies or further full-scale research.

Above all, it is important to note that the choice of a particular technology, or combination of technologies, will always be site-specific. Choices will depend on the characteristics of a given WWTP, the micropollutant concentrations and the presence of bromide in the influent, as well as limitations some WWTPs face in access to power supply (grid connection). Available budget and sustainability objectives will also play a role. Tailored assessments must therefore be made for each WWTP to determine the optimum solution.

Mark van der Werf
STOWA Director

ABBREVIATIONS

AMR:	Antimicrobial resistance, antibiotic resistance
BACF:	Biological activated carbon filtration
CO_2:	Carbon dioxide
DOC:	Dissolved organic carbon
DWF:	Dry weather flow (to a WWTP)
EBCT:	Empty bed contact time
GAC:	Granular activated carbon
GER:	Gross energy requirement, the gross energy unit of a substance, expressed in primary energy
PE:	Population equivalents at 150 g chemical oxygen demand (COD) per day
IPMV:	Dutch acronym for: Innovation Programme Removal of Micropollutants at wastewater treatment plants
WFD:	Water Framework Directive
NOM:	Natural organic matter
O_3:	Ozone
PAC:	Powdered activated carbon
PACAS:	Powdered activated carbon in activated sludge
PFAS:	Poly- and perfluoroalkyl substances
RWF:	Storm weather flow, or rain weather flow (to a WWTP)
WWTP:	Wastewater treatment plant
SIMONI:	Smart integrated monitoring
STOWA:	Dutch acronym for: the Foundation for Applied Water Research
TRL:	Technology readiness level
TOD:	Total oxygen demand
H_2O_2:	Hydrogen peroxide

SUMMARY

This report presents the evaluation of the Innovation Programme Removal of Micropollutants at wastewater treatment plants (Dutch acronym: IPMV). It provides an overview of the results achieved over the five years duration of the IPMV, from 2019 through 2023. In particular, the findings of 15 pilot studies are summarised and their results compared. The analysis shows that the reference technologies of ozonation and PACAS remain attractive from a cost perspective, while new technologies offer advantages in terms of costs, CO_2 footprint, removal efficiencies and/or nutrient removal.

BACKGROUND

The Chain Approach to reduce pharmaceutical residues in water has been a major driver of efforts to reduce micropollutant emissions in the Netherlands. A key part of the Chain Approach is improving micropollutant removal efficiencies at wastewater treatment plants (WWTPs). To achieve rapid results towards this objective, the responsible Ministry of Infrastructure and Water Management (Min. I&W), the Dutch Foundation for Applied Water Research STOWA (the knowledge centre for the water authorities), various research institutions and the private sector have worked in close collaboration.

The Dutch water authorities have also implemented their own measures to increase micropollutant removal, and practice-oriented innovative research continues to be carried out. The IPMV has played a key role in these efforts. The IPMV was a five-year programme running from 1 January 2019 through 31 December 2023. Its aim was to quickly pave the way for promising new technologies, improvements to existing technologies, and/or innovative combinations of existing technologies. As such, the programme sought to give the water authorities access, within five to seven years, to a wider range of removal technologies, from which they can select the most suitable option(s) for their own WWTPs.

METHODOLOGY

The current report presents an evaluation of 15 pilot technologies investigated within the IPMV. A range of technologies were tested, among them, technologies using powdered activated carbon (PAC), technologies using granular activated carbon (GAC), technologies using other adsorbents (cyclodextrins and high-silica zeolites), oxidative technologies such as ozonation and ultraviolet light with hydrogen peroxide (UV+H_2O_2), filtration technologies, and various combinations of these technologies.

Throughout the programme, a consistent set of cost and CO_2 footprint reference values was applied to enable comparisons to be made across the technologies. These reference values were originally developed in 2018, but were updated to the year 2024 for the purpose of this evaluation. In terms of micropollutant removal efficiencies, comparisons consider not only the 11 Dutch indicator substances, but also the indicator substances defined in the revised EU Urban Wastewater Treatment Directive. This was necessary because the EU indicator substance list differs from the set of indicator substances used within the IPMV protocol.

This evaluation compares the investigated technologies. To support this, and in consultation with the project implementers, design specifications were determined corresponding to a removal efficiency of more than 80% for a minimum of seven of the eleven Dutch indicator

substances (7/11) in the effluent compared to the WWTP influent. Standardising this removal rate allowed comparisons to be made across these technologies with respect to CO_2 footprint and costs. The 80% removal is also aligned with the revised EU Directive, which likewise sets an 80% removal target, albeit based on other substances and measured in every dry weather flow (DWF) sample.

The technologies were compared based on the following:

- micropollutant removal efficiency
- costs
- CO_2 footprint
- ecotoxicity reduction
- nutrient removal
- mitigation of bromate formation
- removal of antibiotic resistance bacteria, PFAS and microplastics
- potential for effluent reuse
- technology readiness level (TRL)

In addition, sensitivity analyses were conducted on cost and CO_2 footprint for a number of parameters, and conclusions and recommendations were formulated for next steps, such as design considerations.

RESULTS

The main results are summarised in the table below, which includes both the reference technologies and the 15 technologies piloted.

TABLE 1 **PERFORMANCE, CO_2 FOOTPRINT, INDICATIVE COSTS, CO-BENEFITS AND TECHNOLOGY READINESS LEVEL (TRL) FOR A STANDARD 100,000 PE WWTP, 2024 REFERENCE VALUES**

Technology	Overall annual performance 7/11 (%)	CO_2 (g CO_2/ m^3 $_{WWTP\ influent}$)	Costs (€/ m^3 $_{WWTP\ influent}$)	Co-benefits	TRL
PACAS reference	80-85	184	0.08 - 0.12		9
GAC reference	80-85	253	0.18 - 0.26		9
Ozonation reference	80-85	77	0.08 - 0.12		9
PAC + cloth filtration	approx. 80	135	0.17 - 0.25	P removal possible	7
PACAS Nereda	80-85	195	0.10 – 0.14		8
BODAC	approx. 80	81	0.14 – 0.22		6-7
Bio-GAC	approx. 80	50	0.12 – 0.18	NH_4 removal, P removal possible	6-7
O3-STEP	approx. 80	125	0.17 – 0.25	NO_3 and P removal possible	8
Upflow GAC - CarboPlus	80-85	161	0.14 – 0.20	P removal possible	8
Upflow GAC - DynaCarbon	80-85	187	0.20 - 0.30	P removal possible	8
Sand filtration (SF) + UV/H_2O_2	75-80	574	0.49 – 0.74	NO_3 and P removal possible	5-6
O_3 + ultrasound	85-90	74	0.08 - 0.12		5
PAC + O_3	approx. 85	144	0.14 - 0.22		7-8
MicroForce	> 80	69	0.17 - 0.25	NH_4 removal	6
Aurea (BO_3)	approx. 85	66	0.13 - 0.19	NH_4 removal, P removal possible	6
DEX filter	80-85	135	0.19 - 0.29	Possible NH_4, NO_3 and P removal[2]	5
AdOx	approx. 75[1]	71	0.12 - 0.18	NH_4 removal with other zeolite demonstrated at lab scale	5
Nanofiltration (NF) + UV/H_2O_2	85-90	183	0.36 - 0.54	Potential for high-value effluent reuse, P removal	5
O_3 + ceramic microfiltration (MF)	approx. 80	167	0.50 - 0.76	Potential for high-value effluent reuse	6

[1] The assumed baseline is 70% at a 100,000 PE WWTP. If a larger share of the total flow is treated, a higher total removal efficiency would be expected. Further research on this technology is still under way.

[2] Further research into the mechanism is needed.

DISCUSSION

In the coming years, water authorities will be required to make informed decisions on the mandatory removal of micropollutants at certain WWTPs, as required under the revised EU Directive. Each authority will determine which technology is most appropriate for its own situation, based on several factors: required removal performance and how it is defined (per sample or per substance groups), costs, CO_2 footprint, additional requirements for N and P removal, potential for effluent reuse, anticipated introduction of individual limits for certain micropollutants under the EU Priority Substances Directive, risk of bromate formation, grid connection requirements and constraints, operational flexibility, use of process additives, space requirements and TRL.

The design specifications, performance criteria, co-benefits and TRL levels outlined in this evaluation can provide key inputs for these decisions, alongside insights gained from ongoing and future demonstration and full-scale experience. While this information is valuable, selection and design of micropollutant removal installations for a specific WWTP will always be an individual decision tailored to site-specific conditions.

The revised EU Urban Waste Water Treatment Directive requires 80% removal in nearly every DWF sample (10 out of 12 or 21 out of 24 samples), based on the concentration in the total effluent versus the concentration in the total influent of the WWTP. This IPMV evaluation is targeted on an average removal efficiency of 80% annually, with the rest of the WWTP (mainly biological treatment) assumed to achieve an average removal efficiency of 40%. In practice, a WWTP's overall removal efficiency will depend on multiple factors, including:

- The actual removal of micropollutants in the WWTP's biological step (this will vary by season)
- The share of the total WWTP flow treated using the selected technology
- The ratio of stormwater to dry weather flow (RWF/DWF)
- Levels of micropollutants, dissolved organic carbon (DOC) and suspended solids in influents

The findings presented in this study should therefore be regarded as indicative. In the coming years, further insights will emerge, particularly about the performance of technologies, both stand-alone and in combination, that have so far only been tested for short periods. Operational experience will also provide greater clarity on the minimum removal efficiencies achieved in individual DWF samples. The cost estimates provided are, likewise, a snapshot based on current knowledge. In practice, costs will vary due to market dynamics, procurement method and site-specific conditions.

A tailored, site-specific assessment will always be needed for every WWTP. For example, it may not be logical to install a PACAS system if the WWTP also faces tighter discharge limits for nutrients, since the full biological treatment capacity would then be needed for enhanced nitrogen and phosphorus removal. In that case, a post-treatment step that targets micropollutants and in some cases also nutrients may be more appropriate.

Additional considerations include whether a new treatment step can be integrated hydraulically into the existing treatment line, whether sufficient capacity is available on the electrical grid and whether influent bromide levels allow for the use of ozonation. Another key question is whether a stand-alone technology is realistic at a particular WWTP, or whether a combination of technologies might provide greater operational flexibility.

The anticipated introduction of individual limits for certain micropollutants under the EU Priority Substances Directive may also influence technology selection.

A key recommendation is therefore to first gain a clear understanding of the site-specific conditions at the WWTP before selecting a technology and developing a design. This should include year-round measurement of WWTP performance, carrying out or commissioning targeted analysis of relevant parameters (e.g., bromide levels), and for lower TRL technologies, pilot testing in real-world conditions.

Beyond removal efficiencies, sustainability considerations also play an important role. Direct nanofiltration does not emerge from this evaluation as immediately attractive as a cost-effective solution with a low CO_2 footprint. However, the technology is capable of producing an effluent of very high quality that can be reused locally as process water or upgraded to drinking water quality. With increasing demand for clean water, this could become an important consideration.

Another important aspect is the development of sustainable non-fossil PAC and GAC. In particular, progress towards more sustainable PAC could significantly reduce the CO_2 footprint of this raw material. For implementation, it will be essential to have reliable data on availability, performance, costs and CO_2 footprint of non-fossil PAC. Sensitivity analysis with non-fossil PAC indicates that the impact of more sustainable PAC on overall CO_2 footprint could be very significant.

Finally, the availability of a sufficiently large power connection and/or grid capacity is a critical site-specific factor. Where grid capacity is limited, technologies with high electricity demands will not be feasible.

CONCLUSIONS AND RECOMMENDATIONS

Within the IPMV, many technologies were developed and advanced to technological maturity (higher TRLs) within a relatively short period of time. Some technologies, however, still require further research. These include the DEX filter, AdOx, NF + UV/H_2O_2, O_3 + ultrasound and SF + UV/H_2O_2. For these technologies, open research questions remain or optimisations are needed before they can be applied full-scale at a WWTP. The same holds for membrane-based technologies.

Most of the technologies investigated achieved a removal efficiency of 80% or higher for 7/11 Dutch indicator substances, on an annual average basis and measured over the total effluent versus the total influent of the WWTP.

Depending on the removal mechanisms of the combined technologies and the dosages applied, combinations may or may not result in higher removal of a wider range of substances (the so-called ‘broader palette’) compared to stand-alone technologies. Higher removals will be achieved only if one removal mechanism targets particular substances more effectively than the other mechanism. For example, diclofenac is efficiently removed with ozonation, but much less so by PACAS.

Whether the technologies with the design specifications applied in this evaluation ultimately comply with the revised EU Urban Wastewater Treatment Directive will depend on how the Directive, including sampling requirements, will be embedded into Dutch legislation. Key differences between the IPMV approach and the EU Directive include the IPMV's use of annual averages versus a minimum removal efficiency per sample in the EU Directive. The Directive also applies different indicator substances, taking into account not only those with the highest removal efficiencies (as in the IPMV), but also their distribution across two categories. Given these differences, for compliance it is not only the minimum removal efficiency in the WWTP plus the applied post-treatment technology that matters, but also the 'breadth' of removal across both EU substance categories. It is therefore recommended that the impact of these categories, along with the need for flexibility to meet future minimum performance requirements set by the regulator, be taken into account in the multi-criteria assessment process for technology selection.

Regarding costs, these vary across the investigated technologies. For most technologies using PAC, GAC and/or ozonation, indicative costs range from €0.10 to €0.25 per m^3 WWTP influent, based on a 100,000 PE scale. Membrane technologies (NF + UV/H_2O_2 and O_3 + ceramic MF) are more expensive, but offer the added benefit of producing high-quality effluent suitable for reuse as, for example, industrial water. New adsorbents, such as cyclodextrins and high-silica zeolites, require further research before their cost-effectiveness and removal efficiencies can be reliably determined.

Combined technologies provide greater flexibility in meeting discharge standards because they offer more process parameters that can be adjusted. This could make it easier to comply with removal targets during periods in which the biological removal performance is low. However, combined technologies tend to have higher foundation costs than stand-alone technologies. PACAS has the lowest foundation costs and, along with ozonation, the lowest cost per cubic metre. In terms of annual operating costs, combined ozonation and activated carbon systems are significantly more expensive than the stand-alone solutions.

The CO_2 footprint per m^3 WWTP influent was quantified and lies between 50 and 200 g CO_2/m^3 influent. Some technologies, such as SF + H_2O_2/UV, have a considerably greater CO_2 footprint. The principle of biological activated carbon filtration (BACF), applied in BODAC, Aurea (BO_3) and Bio-GAC, offers opportunities for reducing the CO_2 footprint of micropollutant removal. Yet, while promising, BACF still remains to be proven at full WWTP scale and across different effluent compositions. Overall, seven of the investigated technologies achieved a CO_2 footprint below 85 g CO_2/m^3 WWTP influent, and thus can be considered in the low category. These are BACF (BODAC, Aurea (BO_3) and Bio-GAC), the ozonation reference, MicroForce, AdOx and O_3 + ultrasound. If Dutch renewable ('green') electricity is assumed instead of fossil-based ('grey') power, eight technologies fall below 50 g CO_2/m^3 WWTP influent.

A major added value of the IPMV pilots was the development of a methodology for measuring and assessing ecotoxicity. Due to cost and time constraints, however, only a limited number of ecotoxicity tests were carried out per pilot. Nonetheless, results show an average reduction in ecotoxicity of 50% or more across the total WWTP effluent for all technologies. For PACAS and GAC filters, the reduction was around 50%, while for combined technologies, such as PAC + O_3, MicroForce and SF + UV/H_2O_2, reductions of up to 75% were achieved.

For ozonation, the required micropollutant removal can be achieved at a relatively low cost and modest CO_2 footprint. A drawback, however, is the possible formation of bromate from bromide in the influent. During the IPMV, extensive experience was gained with both the possibilities and the limitations of mitigating bromate formation. In addition to influent bromide levels, both the required ozone dose and the method of application are critical factors. Low ozone dosages in combination with fine-bubble diffusers can significantly reduce the risk of bromide formation. The combinations of technologies considered in this study that include an ozone-based component leverage this by applying lower ozone doses than stand-alone ozonation systems. In the case of O3-STEP, any bromate formed in ozonation is subsequently reduced under anoxic conditions in the GAC filter.

The development of BACF (BODAC, Bio-GAC, Aurea (BO_3)) for advanced micropollutant removal is a key achievement of the IPMV. BACF enables the use of GAC filters with both a low CO_2 footprint and low operating costs, provided that the expected service life of 15 years can be achieved in practice. This still needs to be verified under operational conditions. Depending on the WWTP, BACF can be applied either as a stand-alone solution or in combination with ozonation, with the latter option offering the benefit of significantly reduced ozone consumption.

The MicroForce concept, which uses a high-density polyethylene (HDPE) carrier material instead of granular carbon, is also promising. Its low ozone demand, combined with biological degradation, results in both low treatment costs per m^3 and a relatively small CO_2 footprint.

Several technologies can remove not only pharmaceuticals, but also other substances, such as nutrients. Given the scale of the Water Framework Directive challenges, this presents a valuable opportunity for integrated solutions. It may justify selection of a specific technology, or combination of technologies, as an alternative to, or in addition to, nutrient removal optimisation in the water line.

Membrane filtration technologies combined with oxidation are particularly well suited for high-value effluent reuse while simultaneously removing micropollutants. For WWTPs with high-value effluent reuse objectives, these technologies can be integrated relatively easily and simultaneously achieve micropollutant removal aims.

Finally, the sensitivity analysis shows that sustainability measures, such as use of renewable electricity and more sustainable PAC, can substantially improve the CO_2 footprint of certain technologies. In some cases, this improvement is enough to shift their relative ranking in the evaluation.

STOWA IN BRIEF

WATER KNOWLEDGE, FOR NOW AND THE FUTURE

The Foundation for Applied Water Management Research – STOWA for short – is the knowledge platform for regional water managers in the Netherlands. From our office in Amersfoort, we develop, collect, disseminate, and implement applied knowledge. Water managers need this knowledge to effectively address the challenges they face, whether it concerns climate adaptation (both urban and rural areas), good water quality, sustainable and effective wastewater treatment, safe dikes and embankments, energy transition, or the circular economy.

The type of knowledge we develop is broad: technical and scientific, but sometimes also administrative-legal or social science. To ensure that this knowledge can be applied effectively in practice, we present our research results, where possible, in the form of practical guidelines, tools, and instruments. We also facilitate Communities of Practice to facilitate knowledge transfer and organize various meetings and webinars for this purpose. We provide background information on our work through our own and third-party media.

STOWA operates demand-driven. We identify the knowledge needs of water managers and escalate these questions to the appropriate knowledge providers: universities, knowledge institutes, knowledge companies, or consultancy firms. We handle the tendering and supervision of joint knowledge projects. However, we ensure that water managers remain involved in these projects and also retain ownership. This ensures that the project results offer participants practical action perspectives. Each project is therefore supervised by a committee consisting of regional water managers themselves. The broad research lines are determined by program committees, which also include water managers.

STOWA is independent, impartial, and transparent. Those who use our knowledge must be able to trust that the content of our reports is objective and representative. Only then can our knowledge be applied to better water management and innovations that address the challenges of today and tomorrow. It is up to water managers to determine how they apply STOWA's knowledge in practice.

STOWA is a foundation that adheres to the guidelines for non-profit organizations (RJ-640). That's why our annual report includes, in addition to the financial statements, a management report on the foundation and its activities. The annual budget is approximately €20 million. Our members collectively contribute approximately €10 million annually as a structural contribution. In addition, we receive approximately €10 million annually in contributions to individual projects.

EVALUATION INNOVATION PROGRAMME REMOVAL OF MICROPOLLUTANTS AT WASTEWATER TREATMENT PLANTS

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INTRODUCTION

1.1 IPMV BACKGROUND

The presence of micropollutants in water is of growing concern worldwide. These substances are increasingly detectable, and new polluting substances are continually being identified. Many of these pollutants end up in sewer systems and are not fully removed during wastewater treatment. This means they eventually end up in surface waters, where they pose risks to public health, drinking water production and ecological water quality.

In the Netherlands, a number of initiatives have been launched under the Chain Approach to reduce pharmaceutical residues in water. Part of the Chain Approach is to improve the micropollutant removal efficiency of wastewater treatment plants (WWTPs). To achieve rapid results towards this objective, collaborative efforts have been carried out involving the responsible Ministry of Infrastructure and Water Management (Min. I&W), the Dutch water authorities, the Foundation for Applied Water Research STOWA (the knowledge centre for the water authorities) and various research institutions, as well as the private sector.

The Dutch water authorities have also implemented measures to increase micropollutant removal, and practice-oriented innovative research continues to be carried out. The Innovation Programme Removal of Micropollutants at wastewater treatment plants (Dutch acronym: IPMV) has played a key role in these efforts. The IPMV was a five year programme, running from 1 January 2019 until 31 December 2023.

1.2 IPMV METHODOLOGY

The objective of the IPMV was to develop technologies for removing micropollutants from WWTP effluent, or to improve existing technologies, in order to achieve significant gains over current method in terms of costs, CO_2 footprint and effluent quality. Attention was also given to potential ancillary benefits ('co-benefits'), such as improved removal of nitrogen, phosphate, PFAS and microplastics; reduction of antimicrobial resistance (AMR) and pathogens; and the potential to reuse effluent.

In 2018, water authorities conducted an inventory to identify technologies that should be further investigated. In 2020, four additional technologies were added following a public call for proposals. This second call stipulated a higher removal efficiency threshold (80% instead of 70% for 7/11 indicator substances relative to WWTP influent), as well as a greater emphasis on a low CO_2 footprint. The IPMV's aim was to develop technologies that could be implemented at demonstration scale at WWTPs by 2027.

Each project within the IPMV began with a theoretical feasibility study to substantiate the technology concept and the expected effluent quality, costs and CO_2 emissions for a standard WWTP in the Netherlands (with a capacity of 100,000 PE).

If the technology was sufficiently justified and expected to perform better than the PACAS, ozonation or GAC reference cases, it could proceed to a pilot phase. This resulted in 22 feasibility studies and 15 pilot projects during the five years of the IPMV.

During the IPMV, a number of other studies were added following discussions within the thematic advisory committees, the overarching supervisory committee and the programme's steering group. These included the addition of PFAS and antibiotic resistance analyses to the pilot projects, research into robust sampling methods, oxidation products, PAC measurement in WWTP effluent, exploration of micropollutant release during sludge digestion and exploration of natural treatment systems for micropollutant removal (see appendix 1 for a list of these studies).

1.3 IPMV EVALUATION

Following its conclusion on 31 December 2023, the IPMV was updated and evaluated in 2024. Throughout the IPMV's five years, the same cost and CO_2 reference values were used so that comparisons could be made across the various findings. These reference values, originally set in 2018, were updated in 2024 to reflect the most recent figures. The evaluation also included a comparison with the proposed methodology for assessing micropollutant removal in the revised EU Urban Wastewater Treatment Directive, as this differs from the protocol with indicator substances used by the IPMV.

Furthermore, the evaluation compared the investigated technologies. For the purpose of this comparison, in consultation with project implementers, design specifications were determined to achieve a removal efficiency of more than 80% for a minimum of seven of the eleven (7/11) Dutch indicator substances in the total effluent compared to the total WWTP influent. By standardising this level of removal, comparisons of CO_2 and costs became more straightforward and also aligned more closely with the revised EU Directive, which also aims for 80% removal, albeit for a different set of substances.

The evaluation also examined design assumptions, co-benefits, TRLs and knowledge gaps regarding scale-up, optimisation and/or outstanding research questions. Finally, conclusions were drawn and recommendations formulated.

1.4 STRUCTURE OF THE REPORT

This report provides an overview of the innovative technologies investigated within the IPMV as highlights both their similarities and differences. The technologies are relevant for Dutch WWTPs that will be required to remove micropollutants. The evaluation is therefore primarily intended for policymakers, advisors, technologists and other experts, and assumes a solid knowledge of the field.

The results presented in this report are indicative and intended to provide insight into the various technologies, for example, to support technology selection and the associated criteria in a multi-criteria assessment. It is important to note that such decisions must always be tailored to, and evaluated on, a site-specific basis. Moreover, most of the technologies described in this report continue to evolve, and increasing amounts of practical experience will become available over time to confirm, refine or further optimise the information presented here.

2

ASSUMPTIONS

2.1 SCOPE

The present evaluation addresses a set of quantitative and qualitative factors, as listed in Table 2.1.

TABLE 2.1 **CRITERIA ON WHICH THE TECHNOLOGIES WERE COMPARED**

Qualitative/Quantitative	Factor	Section in this report
Quantitative*	Removal efficiencies	4.1.1
	CO_2 footprint	4.1.2
	Costs	4.1.3
	Sensitivity analysis: effect of varying cost and design assumptions on CO_2 footprint and/or costs	4.1.4
Qualitative	Bioassays: ecotoxicity	4.2.1
	Co-benefit: nutrient removal	4.2.2
	Mitigation of bromate formation	4.2.3
	Co-benefit: antimicrobial resistance (AMR)	4.2.4
	Co-benefit: PFAS removal	4.2.5
	Co-benefit: microplastic removal	4.2.6
	Co-benefit: effluent reuse	4.2.7

* Based on standard 100,000 PE WWTP, see section 2.3.

The feasibility studies carried out within the IPMV which did not lead to a pilot study (see appendix 1) are not considered in this evaluation. Moreover, other water quality aims, such as those related to the EU Water Framework Directive and projects outside the IPMV, were also not included.

OVERVIEW OF THE TECHNOLOGIES TESTED

The technologies tested in pilot form and included in this evaluation were categorised in an earlier phase according to removal mechanism and are the following:

- Powdered activated carbon (PAC)

1. Powdered activated carbon in combination with cloth filtration (PAC+cloth) (WWTP Vinkel)
2. PACAS Nereda (Simpelveld)

- Granular activated carbon (GAC)

3. Biological oxygen-dosed activated carbon (BODAC) (WWTP Emmen)
4. Continuous Bio-GAC + air (Bio-GAC + air) (WWTP Emmen)
5. O3-STEP without N and P removal (WWTP Horstermeer)
6. Continuous Upflow microGAC (UpflowGAC) (WWTP Hapert)

- Oxidative technologies

7. SF + UV/H_2O_2 (WWTP Aarle Rixtel)
8. O_3 + ultrasound USONiQ (WWTP Winterswijk)
9. PAC + O_3 (WWTP Leiden)
10. O_3 biofilm (MicroForce) (WWTP Walcheren)

11. Biological pretreatment with O_3 (Aurea (BO_3)) (WWTP Horstermeer)
    - Alternative adsorbents
12. Cyclodextrins, DEXSORB, DEX filter (WWTP Lelystad)
13. AdOx, zeolite with filtration (AdOx) (Leiden-Noord)
    - Filtration
14. Nanofiltration with advanced oxidation (NF + UV/H_2O_2) (WWTP Asten)
15. Waterfabriek Ge(O)zond: ozonation with ceramic microfiltration (O_3+ceramic MF) (WWTP Wervershoof)

The same categorisation was also used by STOWA's thematic advisory committees when evaluating the studies. Several technologies, such as O3-STEP, PAC + O_3, SF + UV/H_2O_2, NF + UV/H_2O_2, O_3 + ceramic MF+ and BO_3, apply a combination of removal mechanisms. In this evaluation these combined technologies are categorised under each of the relevant removal mechanisms, as described in Chapter 3, and they are included in multiple comparisons in Chapters 3 and 4.

Several of the technologies aim to remove not only micropollutants but also N and P. For the sake of comparability, the current evaluation focuses primarily on micropollutant removal. However, to provide insight into the impact adding metal salts and methanol on design criteria and CO_2 footprint, this has been addressed in the factsheet for the O3-STEP filter, and the CO_2 footprint was also calculated for O3-STEP including N and P removal.

In this report, longer technology names have been abbreviated as given within parentheses in the list above. Some of the technologies have registered names or patents. For the sake of readability, symbols indicating this (such as ®) have been omitted.

As noted, for each of the pilot studies a feasibility study was first carried out. Appendix 1 lists these, alongside other IPMV feasibility studies and reports.

2.2 STANDARD 100,000 PE TREATMENT PLANT

To enable comparisons across the tested technologies, the results were scaled to a standard WWTP. This standard is defined as having a capacity of 100,000 PE (at 150 g COD/PE/day) and includes primary settling, digestion and biological phosphorus removal with supplemental ferric chloride dosing to achieve an effluent phosphorus quality of 1.0 mg P/l.

The characteristics of this WWTP were derived through expert opinion based on influent characteristics, performance and features of comparable WWTPs from the Dutch water authorities' 2018 benchmarks. These characteristics were further supplemented with information from the database of the Netherlands Statistic Agency (CBS) regarding the purchase of process additives and chemicals, energy consumption and sludge production. See Appendix 2 for further details.

The evaluation thus used a 100,000 PE WWTP model, as defined at the start of the IPMV.

Key characteristics of this standard WWTP are the following:

- Biological capacity 100,000 PE per 150 g COD/PE/day
- Annual influent volume of 7,665,000 m^3/year
- DWF design peak and minimum hydraulic capacity of post-treatment = 1,040 m^3/h
- Effluent quality:
- Total N (annual average) = ≤ 10 mg/l
- Total P (annual average) = ≤ 1 mg/l

2.3 REFERENCE TECHNOLOGIES

The baseline assumptions for the reference technologies were updated based on operational experience gained at WWTPs in the Netherlands (up to the time of writing in 2024). The reference technologies are the following:

- Powdered activated carbon in activated sludge (PACAS)
- Ozonation
- Granular activated carbon filtration (GAC)

At the start of the IPMV, the ozonation reference was defined in combination with sand filtration. The sand filter was intended to support biological conversion of potentially toxic byproducts formed when ozone reacts with organic micropollutants. However, during the IPMV this combination was abandoned, because ozonation alone was found to meet performance requirements, while the sand filter contributed little to byproduct removal (see, e.g., STOWA 2022-47 and STOWA 2022-48).

The costs and performance data for the reference technologies were updated based on full-scale practical experience at WWTPs. This included both WWTPs applying a single, stand-alone technology and those implementing a combined technology approach:

- Dinther (PACAS+ozonation, Waterschap Aa en Maas)
- Groesbeek (PACAS, Waterschap Rivierenland)
- Hapert (ozonation (with peroxide), Waterschap De Dommel)
- Horstermeer (ozonation, with GAC already present, Waterschap Amstel, Gooi en Vecht)
- Houten (ozonation, Hoogheemraadschap De Stichtse Rijnlanden)
- Leiden Noord (PACAS, Hoogheemraadschap van Rijnland)
- Nieuwe Waterweg (PACAS, Hoogheemraadschap van Delfland)
- Oijen (PACAS, Waterschap Aa en Maas)
- Wervershoof (ozonation, Hoogheemraadschap Hollands Noorderkwartier)
- Winterswijk (ozonation + GAC, Waterschap Rijn en IJssel)

For the abovementioned WWTPs, removal efficiencies, energy demand, process input/ chemical consumption, and costs (construction and foundation costs) were collected and documented where available. The results for the reference technologies are included in the factsheets in appendix 5.

Section 3.13.1 presents the updated overview for the reference technologies. ,

2.4 MICROPOLLUTANT REMOVAL

2.4.1 IPMV AND THE DUTCH 'TREATMENT OF MEDICINE RESIDUES' CONTRIBUTION SCHEME

Within the IPMV, removal efficiency is defined as the arithmetic mean of the individual removal efficiencies of 7/11 indicator substances (Table 2.2) across the entire WWTP. That is, a comparison is made between the effluent (the discharged water) and the influent. The target was first set to achieve an annual average removal of 70% (IPMV first round) and later revised to 80% (IPMV second round, starting in 2020).

The indicator substances and the 70% removal target are aligned with the Dutch contribution scheme 'Incentive Scheme for the Removal of Pharmaceutical Residues: First Round', initiated by the Ministry of Infrastructure and Water Management (Min. I&W 2023). Under this scheme, however, a minimum removal efficiency of 70% must be achieved in every sample. At the request of STOWA and the Ministry, a collaboration of the Dutch water authorities and government laboratories (the ILOW laboratories) developed a validated analytical method with defined performance characteristics for 11 indicator substances and 8 candidate substances. This method enables the determination of total concentrations of the individual indicator substances at acceptable cost. This analytical method and the sampling of WWTP wastewater for the indicator substances are described in the STOWA report "Robust Sampling Method for WWTPs to Determine Micropollutant Removal Efficiencies" (STOWA 2023-45). The measurement data were used in 2021 to evaluate the indicator substance list, resulting in the removal of three indicator substances from the original list of 11. The study also found that amisulpride, clarithromycin and candesartan were present in too low concentrations in Dutch influents and effluents. These substances were therefore excluded from the most recent national list of 11 Dutch indicator substances (Mulder, 2021).

For the IPMV pilots (and the contribution scheme), it was agreed to analyse all 19 indicator substances in the ILOW analytical package. This broader scope was chosen because some of these substances remain designated as indicator substances in other countries, and for example, are also included in the revised EU Urban Wastewater Treatment Directive.

TABLE 2.2 **ELEVEN INDICATOR SUBSTANCES FOR THE NETHERLANDS AND TWELVE, DIVIDED INTO TWO CATEGORIES, IN CONFORMANCE WITH THE REVISED EU URBAN WASTEWATER TREAMMENT DIRECTIVE**

	Indicator substances NL	Category 1 EU	Category 2 EU
1	carbamazepine	amisulpride	benzotriazole
2	diclofenac	carbamazepine	candesartan
3	hydrochlorothiazide	citalopram	irbesartan
4	metoprolol	clarithromycin	sum of 4- and 5-methyl-1h-benzotriazole
5	venlafaxine	diclofenac	
6	1,2,3-benzotriazole	hydrochlorothiazide	
7	irbesartan	metoprolol	
8	sum of 4- and 5-methyl-1h-benzotriazole	venlafaxine	
9	gabapentin		
10	sotalol		
11	trimethoprim		

* The additional 8 substances in the 19-substance ILOW analytical package are amisulpride, azithromycin, candesartan, citalopram, clarithromycin, furosemide, propranolol and sulfamethoxazole.

** The substances in blue are not included in the Dutch list of 11 indicator substances, as these are typically present in (too) low concentrations in influent and effluent in the Netherlands.

To calculate the removal efficiency across the entire WWTP, the IPMV assumes for most technologies an average removal of 40% in the activated sludge process for 7/11 indicator substances (see Appendix 2). It is possible that the 7/11 substances most effectively removed in the WWTP do not exactly match the 7/11 most effectively removed by a post-treatment technology.

2.4.2 EU DIRECTIVE

The revised EU Urban Wastewater Treatment Directive provides that larger WWTPs (those serving more than 150,000 PE) and WWTPs discharging into sensitive waters will, in time, be required to remove micropollutants (see, e.g., EU 2024). The definitive sampling and analytical methodology has not yet been defined in Dutch legislation. For the Netherlands, STOWA has developed a protocol (STOWA 2023-45) that is somewhat differed from the sampling procedure set out in the revised EU Directive.

In accordance with the EU Directive, removal is calculated based on the arithmetic mean removal of the selected substances in 24- or 48-hour composite samples taken on dry weather days (DWF) and on the basis of concentrations. The removal efficiency must be at least 80% across the entire WWTP, with only a limited number of exceedances allowed per sample.

The revised EU Urban Wastewater Treatment Directive stipulates that the removal percentage must be calculated over at least six of twelve substances, with a mandatory 2:1 ratio between substances from category 1 and category 2 (see Table 2.2).

The current evaluation provides an indicative estimate of removal efficiencies for the substances listed in the EU Directive, for both the reference technologies and the 15 innovative technologies. As for the IPMV protocol, this estimate is based on annual average removals, not on whether each individual sample achieves the 80% efficiency threshold.

2.5 CO_2 FOOTPRINT

The CO_2 footprint has been calculated for all technologies in accordance with the model 'CO_2 Footprint WWTPs Micropollutants 100,000 PE'. The CO_2 emission factors used in previous STOWA reports on the pilot systems date from early 2019, based on the information available at that time (2018). As a result, the CO_2 emission factors published in those STOWA reports reflect the situation in 2018.

For the current evaluation, the 2018 assumptions with respect to CO_2 footprint have been updated to 2024. The updated figures were sourced from www.emissiefactoren.nl and reflect 'well-to-wheel' values, meaning they include both upstream (indirect) and direct emissions. This method is consistent with the methodology used in the CO_2 Performance Ladder and the water authorities' climate monitor. Appendix 3 elaborates further on the background and data sources.

TABLE 2.3 **CO_2 EMISSIONS REFERENCE VALUES, 2018 AND 2024**

Parameter	Unit	IPMV 2018	Updated 2024
Electricity	kg CO_2/ kWh	0.53 [1]	0.536 [3,4]
Natural gas	kg CO_2/ Nm^3 natural gas	1.79 [1]	2.134 [3]
Diesel fuel	kg CO_2/ kg diesel	2.21 [1]	3,256 [3]
Heat	kg CO_2/ GJ heat	64.9 [1]	74,1 [3,5]
Transport	kg CO_2/ ton*km sludge transport	0.13 [1]	0.105 [3,6]
Final sludge treatment	kg CO_2/ kg dewatered sludge	0.05 [2]	0.05 [7]
Reinforced concrete	kg CO_2/m^3 reinforced concrete	133 [1]	329 [8]
Conversion factor for process additives/chemicals	kg CO_2/Gj primary	58.84 [1]	67.28 [3]
Process additives/chemicals (see Appendix 3)			
Activated carbon	kg CO_2/ kg	9.60	11.06
Regenerated activated carbon	kg CO_2/ kg	2.52	2.90
Activated carbon of biological origin	kg CO_2/ kg	3.94	4.52
Hydrogen peroxide (50%)	kg CO_2/ kg	1.21	1.53
Oxygen, liquid	kg CO_2/ kg	0.42	0.59
Polymer, cationic, liquid (100% active)	kg CO_2/ kg	3.90	4.49

[1] Emissions reference values 2018.

[2] Average based on environmental annual reports GMB, SNB and HVC 2017.

[3] Emissions reference values 2024.

[4] Non-renewable ('grey') = 0.536 (This factor represents the average CO_2 emissions of non-renewable electricity, including upstream emissions. The sensitivity analysis used 0 kg CO_2/kWh for renewable ('green') electricity in the Netherlands.

[5] Primary energy of heat is 1.1 $GJ_{primary}/GJ_{heat}$ (Climate Monitor report year 2022).

[6] CO_2 emissions coefficient for transport by lorry >20 tons plus trailer (load capacity 28 tons).

[7] Based on the same value as in 2018.

[8] Environmental impact of full LCA of continuously reinforced concrete C30/37 CEM III (https://milieudatabase.nl/nl/rapporten-tool/report/33/).

2.6 COSTS

Within the IPMV, costs were originally calculated based on 2018 price levels, to allow comparisons to be made between and across technologies. Since 2018, however, rising costs have necessitated an update. To provide a realistic picture of the actual costs of micropollutant removal technologies, the current evaluation is based on total foundation costs.

In this evaluation foundation costs were adjusted using the 'Infra-index for Civil and Hydraulic Engineering Works' (Infra-index GWW). Compared to 2018, this index had risen by 38% as of January 2024. Furthermore, all costs were calculated including VAT. Subsidies and other financial contributions were not considered in the calculations. Some technologies are subject to patents or licenses, which may involve additional costs. These costs were not considered in the cost estimates.

In updating foundation costs values originally estimated in 2018, reference projects completed between 2018 and 2024 (using PAC, GAC, ozonation and combinations thereof) were also considered. If the costs of these reference projects deviated significantly from the updated estimates, then the reference project costs were taken as leading.

The method of procurement also impacts foundation costs. One option is an approach with a joint client-contractor team in which a water authority, consultant, contractor and technology supplier jointly develop a design and implement the technology. Alternatively, technology suppliers may be invited to submit bids based on specifications defined by a water authority. This factor is addressed in the sensitivity analysis.

Tables 2.4 through 2.6 present the updated cost reference values. These reflect current prices for labour, energy, and process additives as obtained from the collaborating water authorities and implementation partners.

TABLE 2.4 MARKUP PERCENTAGES FROM BASE CONSTRUCTION COSTS TO FOUNDATION COSTS

Parameter	Value	Explanatory notes
Contractor costs	25%	Applied to base construction costs for civil, mechanical, electrical and process automation works. This includes the contractor's execution costs, such as general site costs, implementation costs, overhead, profit and risk.
Allowance for estimate incompleteness	25%	Applied to the base construction costs, including contractor's costs, to account for incomplete scope or underestimations in the cost estimate.
Additions	80%	Covers VAT, unforeseen items, engineering, project management, site supervision, insurance, temporary facilities during conversion and start-up, training and communication.

* This results in a total multiplication factor of 2.81 to convert base construction costs into total foundation costs (1.25*1.25*1.8).

TABLE 2.5 CALCULATION OF ANNUAL COSTS

Parameter	Value	Unit
Capital expenditures (linear depreciation method)		
- Civil works (C)	30	years
- Mechanical (W)	15	years
- Electrical (E)	15	years
- Process automation (PA)	5	years
Interest	4	%
Maintenance costs		
- Civil works	0.5	% of construction costs
- W/E/PA	3	% of construction costs

TABLE 2.6 OPERATING COSTS (INCLUDING VAT)

Parameter	Unit	IPMV 2018	Updated 2024
Personnel costs	FTE/y	€ 50,000	€ 80,000
Electricity	kWh	€ 0.10	€ 0.20
Polymer	kg purchased product (50% active)	€ 3.00	€ 3.00
Pure oxygen	kg	€ 0.20	€ 0.19
Ferric and aluminium chloride	ton (40% w/w)	€ 120	€ 300
Powdered activated carbon	kg	€ 2.00	€ 2.75
Granular activated carbon	m^3	€ 1,200	€ 1,350 *
Regenerated granular activated carbon	m^3	€ 500	€ 900
Methanol	ton (100% w/w)	€ 355	€ 550
Backwash water production	m^3	€ 0.04	€ 0.04
Backwash water treatment at WWTP	m^3	€ 0.01	€ 0.01
Sludge removal	ton DS	€ 600	€ 600
NaOH (membrane process)	kg (50% w/w)	€ 0.225	€ 0.37
NaOCl (membrane process)	kg (15% w/w)	€ 0.40	€ 0.55
Citric acid (membrane process)	kg (50% w/w)	€ 1.7	€ 2.35
Antiscalants (membrane process)	kg	€ 1.2	€ 1.66
H_2O_2	kg (50% w/w)	€ 0.5	€ 0.69
DEXSORB adsorbent	ton	€ 10,000	€ 13,800
Regenerated DEXSORB adsorbent	ton	€ 6,000	€ 8,280
DEXSORB disposal	ton	€ 1,000	€ 1,380
Zeolite	kg	€ 27	€ 25

* €3,000/ton and 450 kg/m^3.

Cost estimates are business-economics based, meaning that market conditions have not been factored in. However, market conditions can result in actual costs varying significantly from the projected estimates. This is linked to the business cycle: in times of economic expansion, bids often exceed cost estimates (e.g., when there is high demand in the market or raw material prices are elevated). During economic downturns, bids are typically lower. Not accounting for market effects may, for instance, lead to bids that exceed the budget or the specified ceiling price—potentially by a substantial margin.

Over the past six years, indexation was approximately 6% per year. Given current market indicators, it seems realistic to expect this trend to continue in the coming years.

- Investments in the wastewater treatment and drinking water sectors are expected to rise considerably in the years ahead. For Dutch WWTPs, this is due, for example, to measures for compliance with the EU Water Framework Directive with regard to surface water quality, the need to remove pharmaceutical residues, and actions to comply with the revised EU Urban Wastewater Treatment Directive.
- Moreover, there is a scarcity of certain raw materials.
- Technical personnel are scarce.

2.7 ECOTOXICOLOGICAL RISKS

In addition to the criteria discussed above, wastewater treatment must also achieve a reduction in ecotoxicological risks. The target in this regard is to reduce the risks to the aquatic environment from WWTP effluent discharges by at least 50%.

Ecofide (2023) presents guidelines for biological effect monitoring of advanced-treated WWTP effluents, and how results of such monitoring should be interpreted to enable reliable comparisons of different demonstration projects. The conclusions in these guidelines are based on an evaluation of monitoring results from 13 water authorities and several other studies that applied the methodology from an earlier, 2020, version of the guidelines. Based on these measurements, the earlier guidelines were revised to a more recent, 2023, version.

2.8 CO-BENEFITS

The pilot studies focused primarily on micropollutant removal. For some technologies, however, there is evidence of additional ‘co-benefits’. In other words, they also remove other substances:

- Total nitrogen (total N)
- Ammonium
- Total phosphorus (total P)
- Microplastics
- *E. coli* and other pathogens (disinfection)
- PFAS
- Antimicrobial resistance (AMR)

In some pilot studies, it was possible to investigate these co-benefits (see introduction). Moreover, supplementary research was conducted on the removal of PFAS and antimicrobial resistance. The current evaluation includes a summary of the findings from those studies (section 4.2.4 and 4.2.5), and the results are presented in more detail in STOWA reports 2024-29 and 2024-30.

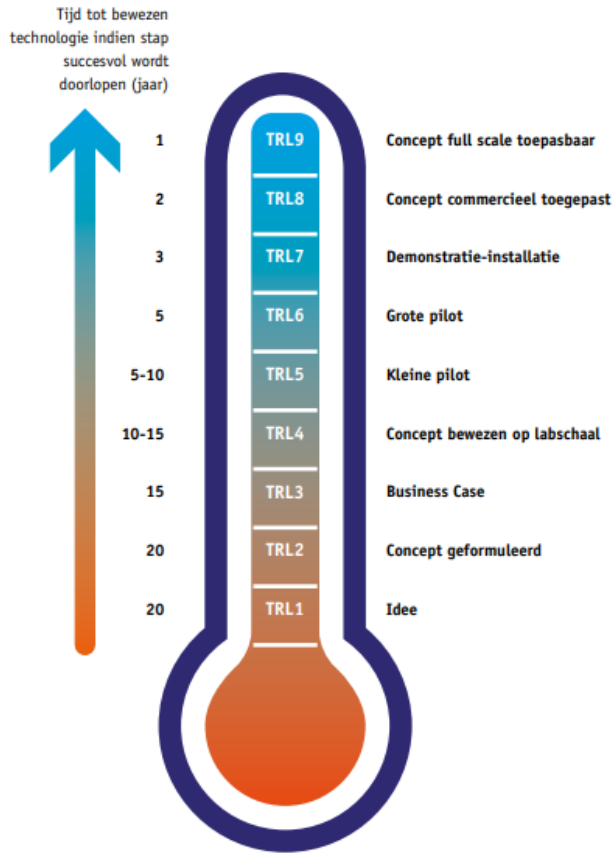
Another potential co-benefit is the ability to reuse effluent. Some technologies were investigated with this objective in mind. However, for these technologies, this report describes and compares only the results aimed primarily at micropollutant removal. Technologies offering the possibility for high-value reuse of effluent often have a much larger CO_2 footprint and significantly higher costs compared to technologies aimed solely to remove micropollutants. Moreover, the benefit of cleaner effluent cannot be readily expressed in terms of costs and/or CO_2 footprint, as their application will be dependent on local conditions.

2.9 TECHNOLOGY READINESS LEVEL (TRL)

The IPMV sought to investigate technologies that could be applied at demonstration scale by 2027. This means that by 2027 the technology readiness level (TRL) of the technology must be at least 7 (Figure 2.1).

Demonstration scale was defined within the IPMV as full-scale application for treatment plants smaller than 25,000 PE. For WWTPs larger than 25,000 PE, at least one treatment line with a minimum capacity of 25,000 PE should be converted.

FIGURE 2.1 **TECHNOLOGY READINESS LEVEL (TRL)**



3

COMPARISON OF TESTED TECHNOLOGIES

3.1 UPDATED REFERENCE TECHNOLOGIES

To enable comparison of the innovative technologies with current practice, three technologies were selected as reference technologies. These were already being applied at full scale in the Netherlands or elsewhere in Europe:

- PACAS (powdered activated carbon in activated sludge): Powdered activated carbon (PAC) is dosed into the existing activated sludge tanks of a WWTP. The PAC, together with the micropollutants adsorbed onto it, is removed with the sludge during sludge settling.
- Ozonation: Micropollutants are broken down into intermediate compounds through the dosing of ozone (O_3).
- GAC filtration (granular activated carbon filtration): Micropollutants are adsorbed onto granular activated carbon in a filter.

The designs for the reference technologies of PACAS, ozonation and GAC were revised in 2024. Compared to those originally defined in 2018:

- PACAS: the main change is that the (fossil) PAC dosage was increased from 15 to 20 mg/l, so the original removal efficiency of 70-75% increases to >80% (based on STOWA 2018-02, STOWA 2023-02). The removal efficiency of PACAS thus becomes comparable with the other two reference technologies (see section 1.3). The absolute improvement in sludge dewatering was reduced from 1.19 to 1 percentage point, and the specific energy consumption was reduced from 12 to 9 W/m^3 treated influent, based on full-scale experience in the Netherlands.
- Ozonation: the specific ozone dose was adjusted from 0.7 to 0.6 g O_3/g DOC (e.g., STOWA 2022-48) and the contact time was shortened from 25 to 20 minutes (e.g., ozonation system at WWTP Houten).
- GAC: In 2018 backwash water was set at 10% of influent flow. This percentage is necessary to also remove nutrients in the filter. Since this was not assumed for the reference, the backwash water was reduced to 1% in the updated figures.

The 2018 GAC reference was based on experiences with the 1-STEP filter at Horstermeer and design assumptions applied in Switzerland. There is currently no full-scale or demonstration-scale GAC system running in the Netherlands, so it is not possible to update this reference using data from more recent experience (except for backwash water volume). This is discussed further in section 3.4.

The sections below provide more detail on the reference technologies. Table 3.1 presents the main design criteria.

TABLE 3.1 **DESIGN CRITERIA FOR REFERENCE TECHNOLOGIES AIMED AT MICROPOLLUTANT REMOVAL[1]**

Parameter	Unit	Value
PACAS		
PAC dosage	mg PAC/l influent	20
Maximum dosage	-	2x DWF
PAC dosage as share of annual flow treated	%	80
Dry solids after dewatering, with:without PAC	% DS	22.1 : 21.1
PE dosage, with:without PAC	g active PE/kg DS	16 : 18
Energy consumption other[2,3]	W/m^3 treated	9
GAC		
Share of annual flow treated	%	70
Contact time (empty bed contact time, EBCT)	minutes	30
Hydraulic loading	m/hour	8
Backwash water	% of incoming flow	1
Carbon service life	months	6
Energy consumption other[2]	W/m^3 treated	0.9
Ozonation		
Share of annual flow treated	%	70
Ozone dose	g O_3/g DOC	0.6
Contact time	minutes	20
Injection method	-	diffusers
Energy consumption ozone production	kWh/kg O_3	10
Energy consumption other[2,3]	W/m^3 treated	30

[1] Based on assumptions for the reference technologies from 2018 (Mulder, 2022) and updated in 2024 to reflect recent operational experiences in the Netherlands and expert judgement.

[2] Energy consumption excludes the pumping of effluent to post-treatment and production of dilution water for PAC preparation in PACAS.

[3] The same value is also applied for calculating 'other' energy consumption in ozone-based technologies. The value of 30 W/m^3 treated is now set independently of the required ozone dose. Actual values may differ depending on practical experience with lower ozone dosages and the design of the specific WWTP.

Table 3.2 presents an updated overview for the reference technologies. For an overview using 2018 reference values, see appendix 3.

TABLE 3.2 PARAMETERS FOR REFERENCE TECHNOLOGIES (UPDATED 2024)

Parameter	Unit	PACAS	Ozonation	GAC[4]
CO_2 footprint				
CO_2 footprint, micropollutant removal	g CO_2/m^3 treated1	184	109	361
CO_2 footprint, micropollutant removal	g CO_2/m^3 WWTP influent	184	77	253
Costs[5]				
Annual costs	€/m^3 treated[1]	0.10	0.10	0.31
Annual costs	€/m^3 WWTP influent	0.10	0.07	0.22
Removal efficiency indicator substances Min. I&W[2]				
Only technology efficiency	%	80-85	80-90	80-90
Efficiency incl. WWTP[3]	%	80-85	80-85	80-85

[1] Per m^3 treated wastewater, in other words, the total costs of CO_2 emissions associated with application of the supplementary technology divided by the number of treated m^3. For PACAS, all incoming wastewater is treated (technology is integrated into the activated sludge system). For post-treatment technologies (ozonation and GAC filter), at least the daily dry-weather peak, in other words, the DWF design peak, must always be treated, as well as 70% of annual volume (which requires the removal efficiency in the treated steam to be high also).

[2] Average removal efficiency for at least 7/11 indicator substances: benzotriazole, carbamazepine, diclofenac, irbesartan, gabapentin, metoprolol, hydrochlorothiazide, 4- and 5-methylbenzotriazole, sotalol, trimethoprim and venlafaxine, in each 24- or 48-hour flow- or time-proportional sample, accounting for 24h residence time of the water in the WWTP. These 11 indicator substances were chosen to monitor the effectiveness of technologies for advanced removal of micropollutants from WWTP influent and have no relation with their potential environmental impact.

[3] Based on an average removal efficiency of 40% in activated sludge for 7/11 Dutch indicator substances.

[4] Excluding nutrient removal.

[5] Annual costs: capital expenditures+ operating costs.

3.2 15 INNOVATIVE TECHNOLOGIES

The 15 innovative technologies are described and compared in the following sections. For this purpose, the technologies have been grouped according to their removal mechanisms. These broadly align with the five technology categories that were defined as key building blocks of the IPMV. A number of technologies can be categorized under more than one removal principle; these are therefore compared with other technologies in more than one paragraph of this report. An example is PAC+O_3, which is discussed under both adsorption onto PAC and under oxidative technologies. The rationale for the classifications is explained in sections 3.3.1, 3.4.1, 3.5.1, 3.6.1 and 3.7.1.

TABLE 3.3 CLASSIFICATION OF TECHNOLOGIES BY REMOVAL MECHANISM FOR COMPARATIVE PURPOSES

Removal mechanism of technology	Subcategory	Note
1. Adsorption onto powdered activated carbon (PAC)		
PAC + cloth filtration		
PACAS Nereda		
PAC+O_3		also included as oxidative technology
2. Adsorption onto granular activated carbon (GAC)		
O3-STEP without N and P removal*	non-aerated	also included as oxidative technology
Continuous upflow GAC	non-aerated	
BODAC	aerated	
Bio-GAC + air	aerated	
Aurea (BO_3)	aerated	also included as oxidative technology
3. Adsorption onto other non-fossil materials		
DEX filter		
AdOx		
4. Oxidative technologies		
SF + UV/H_2O_2		
O_3 + ultrasound		
O3-STEP without N and P removal*	combination of oxidation and activated carbon	also included as GAC technology
PAC + O_3	combination of oxidation and activated carbon	also included as PAC technology
MicroForce	combination of oxidation and biological degradation	
Aurea (BO_3)	combination of oxidation and biological degradation, aerated GAC	also included as GAC technology
NF+H_2O_2	combination of oxidation and filtration	also included as filtration technology
O_3 + ceramic MF	combination of oxidation and filtration	also included as filtration technology
5. Filtration technologies in combination with oxidation		
NF + H_2O_2		also included as oxidative technology
O_3 + ceramic microfiltration		also included as oxidative technology

* The factsheet for O3-STEP also presents information that includes N and P removal. The same applies to the CO_2 footprint.

All the technologies increased in TRL during the five years of the IPMV. Most are now at a stage where they can be implemented at demonstration or even full scale. For five technologies, additional pilots have been set out. This means that the design parameters, energy consumption, efficiency and/or costs presented in this report and in the factsheets are still evolving. Chapter 5 discusses TRLs and the outstanding research questions for these technologies, particularly regarding optimisations, scale-up, performance and specific issues to be addressed in further pilots.

Several general assumptions were applied as part of the 2024 update. The extent to which these hold will, however, depend on the specifics of each WWTP, particularly its location, organizational factors and project-specific circumstances. This regards, for example, staffing, for which 0.5 full-time equivalents (FTE) for a stand-alone technology and 1 FTE for a combination technology is assumed.

Further, a pumping head of 8 m is assumed, unless higher is specified (BODAC, Bio-GAC + air, upflow GAC). No pumping head was included for PACAS or for NF+UV/H_2O_2 because little or no pumping head is required for these technologies. Some technologies are deliberately designed to require a low pumping head, which gives them a slight disadvantage in this calculation approach. The sensitivity analysis therefore includes a range from a very low pumping head of 2 m to the 8 m used in the calculations. The actual pumping head required

is highly site-specific and will depend on both the technology configuration and the local situation.

3.3 ADSORPTION ONTO POWDERED ACTIVATED CARBON (PAC)

3.3.1 TECHNOLOGY CONCEPT AND OPTIMISATIONS

The dosing of activated carbon in powdered form is a proven, cost-effective method for removing micropollutants. Removal takes place via adsorption (binding) of contaminants onto the powdered activated carbon (PAC). The saturated carbon is incinerated together with the sewage sludge. In Germany and Switzerland, PAC is already being applied at full scale at more than 20 WWTPs for advanced removal of micropollutants from wastewater. This can be done in dedicated tanks downstream of the existing treatment, but also by dosing PAC directly into the activated sludge tanks (PACAS).

The PAC reference within the IPMV pertains to the PACAS process, in which powdered carbon is dosed into the biological stage. To achieve the target 80% removal of micropollutants, a dosage of 20 mg PAC/l influent is needed.

Furthermore, the IPMV programme investigated three optimisations of PACAS technology:

- PAC + cloth filtration
- PACAS Nereda
- PAC + O_3

Almost 50% of the CO_2 footprint of PACAS is due to PAC consumption, as this raw material cannot be reused. A key theme within this technology concept is therefore to reduce the CO_2 footprint by using less (fossil-derived) activated carbon or by using carbon with a smaller CO_2 footprint.

For that reason a key objective regarding PAC + cloth filtration and PAC+O_3 was to reduce PAC consumption while maintaining removal efficiency, thereby achieving a lower CO_2 footprint and thus a better score on sustainability. In PAC + cloth filtration, post-treatment dosing of PAC is more efficient than adding PAC to the activated sludge, because the organic components in the effluent are lower than in the activated sludge tank. The PAC+O_3 process combines technologies, and micropollutants are therefore also removed through ozonation. For PACAS Nereda, the objective was to assess the feasibility of applying PACAS in a Nereda (granular sludge) system.

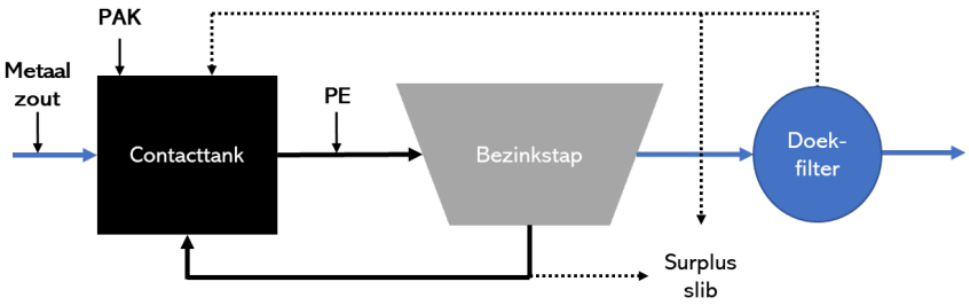
More detailed descriptions of the abovementioned technologies are presented in the factsheets in appendix 5. Summaries and comparisons of the technologies are provided below.

Under the PAC theme, the IPMV also looked at and investigated alternatives to fossil-derived PAC. Additionally, it examined the influence of powdered carbon on the quantity and composition of the sludge to be removed and potential consequences for sludge digestion and further sludge processing. Finally, research was conducted on the extent to which PAC particles end up in WWTP effluent and the subsequent effects. These studies are listed in appendix 1 and are not described further in this chapter.

3.3.2 OVERVIEW OF INNOVATIVE TECHNOLOGIES

PAC + CLOTH FILTRATION

FIGURE 3.1 BLOCK DIAGRAM PAC + CLOTH FILTRATION

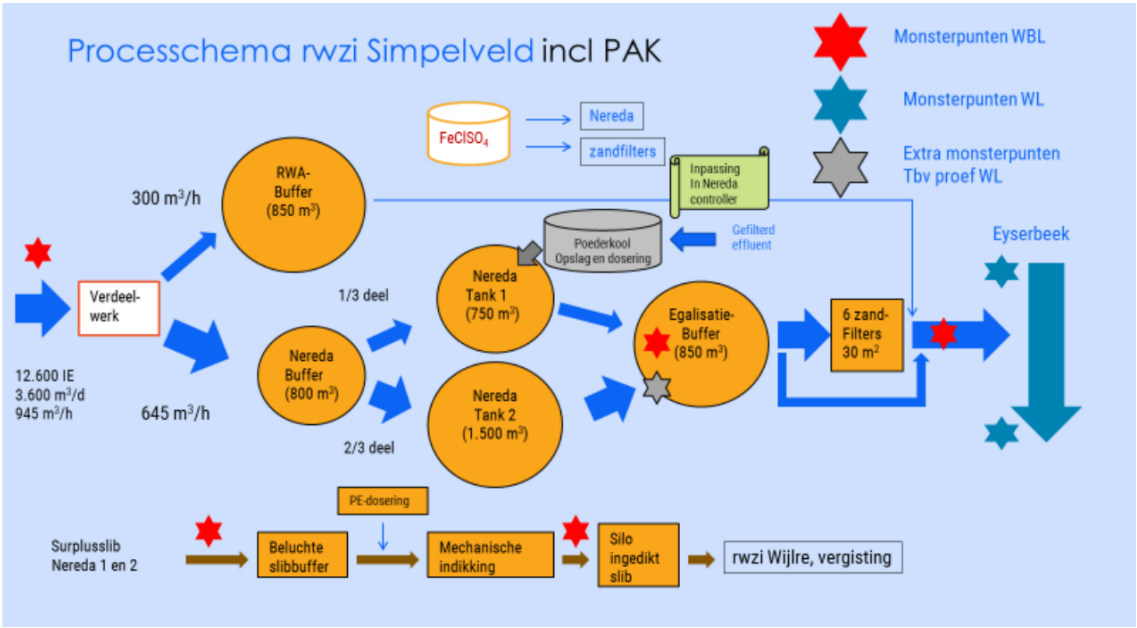


PAC + cloth filtration is a technology in which powdered activated carbon (PAC) is dosed to the effluent of a WWTP in a contact tank. The PAC is then separated from the wastewater by means of a settling step and cloth filtration. Like other adsorption technologies, micropollutants are removed from the wastewater by adsorption onto activated carbon. The addition of a coagulant (metal salt) provides enhanced phosphorus removal while also improving settling and separation of the PAC.

Expected advantages of this technology compared to the reference are a lower PAC dosage requirement and enhanced phosphorous removal. In particular, because PAC + cloth filtration consumes less PAC than PACAS, the technology scores better than PACAS on CO_2 footprint. The process requires both polymer (PE) and metal salt dosing.

PACAS NEREDA

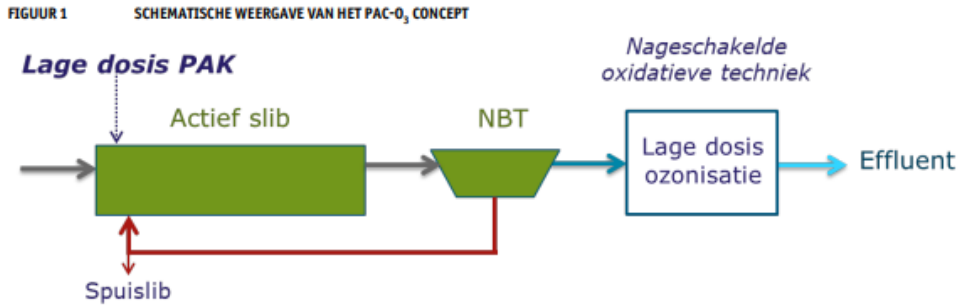
FIGURE 3.2 BLOCK DIAGRAM PACAS NEREDA (BASED ON PILOT AT WWTP SIMPELVELD)



The addition of powdered activated carbon improves the removal of micropollutants and is a relatively straightforward means to remove pharmaceutical residues in a continuously loaded activated sludge system. In PACAS Nereda, powdered carbon is dosed into a granular sludge reactor (Nereda) instead of a conventional active sludge system. Pharmaceutical residues are bound onto the powdered carbon, which is then discharged together with the waste sludge from the Nereda reactor via the regular sludge route (digestion, dewatering, drying and incineration).

PAC + O_3

FIGURE 3.3 **BLOCK DIAGRAM PAC + O_3**



PAC + O_3 is a technology in which powdered activated carbon (PAC) is dosed into the activated sludge process and the effluent is subsequently treated with ozone. The PACAS process is this case is operated with a lower PAC dose, and followed by a post-treatment ozonation step. By making use of two reaction mechanisms, adsorption and oxidation, both can be applied in a less intensive form than if each was utilised as a stand-alone technology.

Expected advantages are a lower PAC dosage compared to PACAS, less bromate formation and a broader palette of substances removed.

3.3.3 COMPARISON

Table 3.4 summarises the main characteristics of the different PAC technologies, including the PACAS reference at a dosage of 20 mg PAC/l. The table shows that PACAS Nereda is very similar to the reference situation. The main differences are that the same PAC dosage has to be applied within a shorter contact time and the PAC pumping head is 6 m. Both factors affect the design of the installation and the energy consumption of the PAC dosing system. The combined technologies PAC + cloth filtration and PAC + O_3 require significantly lower PAC dosages (10 and 7.5 mg PAC/l, respectively) compared to the PACAS reference (20 mg/l). However, in addition to the extra process components, PAC + cloth filtration also requires PE and $FeCl_3$ dosing, which increases sludge production compared to the PACAS reference and PACAS Nereda. A further advantage of $FeCl_3$ dosing is that additional P can be removed. For PAC + O_3, apart from the additional process components, ozone consumption is required.

TABLE 3.4 SPECIFIC DESIGN ASSUMPTIONS FOR ADSORPTION ONTO ACTIVATED CARBON

Parameter	Unit	PACAS reference	PAC + cloth filtration	PACAS Nereda	PAC + O_3
PAC technology					
Dosing location	Main treatment line/ post-treatment	Main treatment line	Post-treatment	Main treatment line	Main treatment line
Treated flow	%	100	70	100	100 (PAC) 70 (O_3)
PAC dosage*	mg/l	20	10	20	7.5
HRT adsorption phase	minutes	-	30	-	-
Lamella surface loading	$m^3/m^2/hr$	-	2.5-4	-	-
Cloth filter	$m^3/m^2/uur$	-	8	-	-
Other dosing					
Fe dosage	mg Fe/l	-	5	-	-
PE dosage	mg PE_{active}/l	-	0.4	-	-
O_3 stage					
Contact time O_3 reactor	minutes	-	-	-	15
O_3 dosage	g O_3/g DOC	-	-	-	0.05
Sludge line					
Sludge production**	kg DS/m^3 treated	0.016	0.025	0.016	0.006
PE use for dewatering	g active PE/kg DS	16	18	16	17
Final DS	%DS	22.1	21.6	22.1	21.6
Energy consumption					
Total	kWh/ m^3 treated	0.009	0.063	0.030	0.145***
Technology excl. pumping and backwash water	kWh/ m^3 treated	0.009	0.018	0.030	0.110***
Pumping 8 m pumping head	kWh/ m^3 treated	-	0.035	-	0.035
Backwash water	kWh/ m^3 treated	-	0.010	-	-

* Dosage corresponding to 80% removal of 7/11 indicator substances relative to WWTP influent.

** For PACAS (reference, PACAS Nereda and PAC+O_3) dosing is capped at 2x DWF, so the stated dose applies to 80% of the annual flow.

*** Specific consumption was calculated using the flow of the post-treatment technology: 5,365,500 m^3/year.

3.4 ADSORPTION ONTO GRANULAR ACTIVATED CARBON (GAC)

3.4.1 TECHNOLOGY CONCEPT AND OPTIMISATIONS

Unlike powdered activated carbon (PAC), granular activated carbon (GAC) is in granular form. When placed in a carbon filter downstream of an existing treatment line, these granules adsorb micropollutants. No additional filtration step is needed to separate the granular carbon from the treated water, though such a step is required with post-treatment PAC dosing. Furthermore, saturated GAC can be regenerated, which is not possible with PAC. Other differences are that bacteria can grow on the granular carbon and contribute to the degradation of micropollutants, and removal of macropollutants such as phosphate and nitrogen can be stimulated by dosing supplementary chemicals onto the GAC filter. However, the effect of supplementary chemical dosing on carbon adsorption capacity is not yet fully understood.

In the Netherlands, the first full-scale GAC filter was constructed at WWTP Horstermeer. This filter removes both phosphate and nitrogen, as well as micropollutants, in a single step through the addition of methanol and metal salts. For that reason, it was named the '1-STEP filter'. In practical applications, the 1-STEP filter has been proven effective for removing both micro- and macropollutants. However, the service life for micropollutant removal is short; the filter's removal efficiency for micropollutants drops sharply after only three months, although nutrient removal remains high. This makes application of the technology relatively expensive, because the carbon has to be regenerated relatively often. The O3-STEP

filter investigated within the IPMV combines a low ozone dose ozonation with a 1-STEP filter, which extends the service life of the activated carbon.

The main challenge under this theme is to improve filter performance for micropollutant removal while extending the service life of the GAC. This would reduce costs and increase the overall effectiveness of the technology. Within the IPMV, this has been addressed by exploring optimisations such as upflow filters with (micro)GAC and actively aerated biologically driven GAC filters (biological activated carbon filtration, BACF).

Depending on the configuration, a contact time (EBCT) of 30 to 60 minutes is required to achieve 80% removal of micropollutants with a service life of approximately 1 year. Within the IPMV, five optimisations of the GAC concept were investigated, broadly divided into the non-aerated and aerated systems:

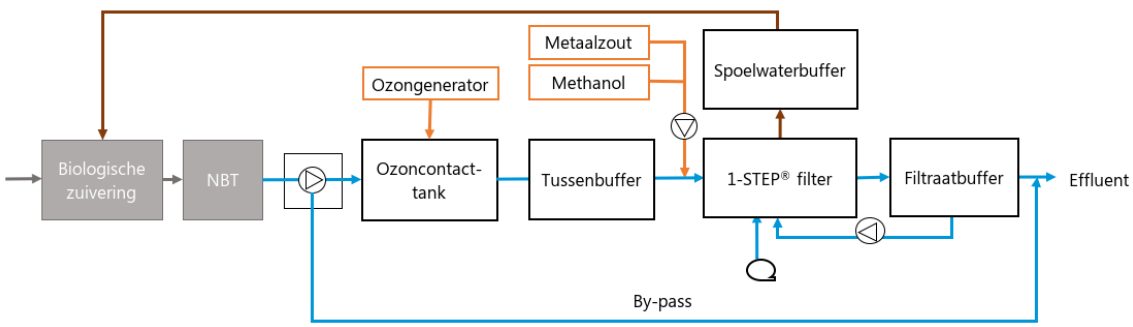
- O3-STEP (non-aerated)
- Continuous upflow GAC (non-aerated)
- BODAC (aerated)
- Continuous Bio-GAC + air (aerated)
- Aurea (BO_3) (aerated)

More details on these technologies are presented in the factsheets in appendix 5. A summary of each technology is provided below.

3.4.2 OVERVIEW OF INNOVATIVE TECHNOLOGIES

O3-STEP

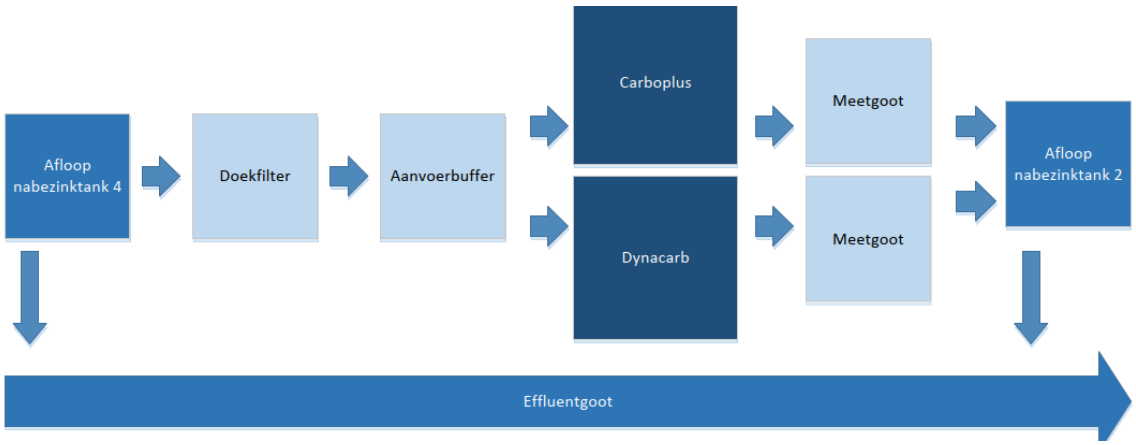
FIGURE 3.4 BLOCK DIAGRAM O3-STEP



The O3-STEP filter is a further evolution of the existing 1-STEP filter technology in which post-treatment takes place via fixed-bed filtration with GAC as both the filtration and the adsorption medium. In the 1-STEP filter, several different processes occur: adsorption onto GAC, biological degradation, denitrification and phosphate removal by coagulation and flocculation, and filtration. In the O3-STEP filter, an ozonation step is added prior to the 1-STEP filter to partially oxidise organic (micro) pollutants, such as pharmaceutical residues. The expected advantages compared with the reference are a higher removal efficiency for a broader range of micropollutants (see appendix 6), increased service life of the activated carbon, mitigation of bromate formation and a comparable (or slightly improved) CO_2 footprint and indicative costs. A key finding from the pilot study is that any bromate formed by ozonation, can be degraded under anoxic conditions in the denitrifying GAC filter (see section 4.2.3).

CONTINUOUS UPFLOW GAC

FIGURE 3.5 BLOCK DIAGRAM UPFLOW GAC



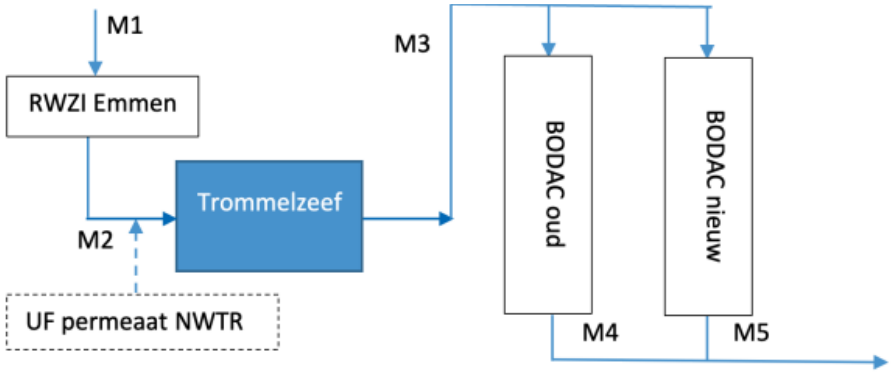
Unlike a conventional GAC filter, the upflow GAC filter is fed from the bottom and flows upward. Due to the upward flow, the activated carbon remains in motion, resulting in improved contact between the activated carbon and the water.

Within the IPMV, two upflow GAC filters were tested: CarboPlus and DynaCarbon. The CarboPlus system is a fluidised-bed activated carbon filter in which several times per week, depending on the (waste)water treated, fresh activated carbon is added and saturated carbon is removed. This enables continuous operation of the filter. The DynaCarbon system is a moving-bed reactor in which activated carbon is added once then continually washed using a mammoth pump. The GAC is replaced once adsorption capacity becomes too low to effectively remove micropollutants.

The expected advantage of the technology compared to the GAC reference is improved contact between the activated carbon and water, which enables high removal efficiencies to be achieved with a lower CO_2 footprint, especially if as much fresh carbon as possible is replaced by regenerated carbon.

BODAC

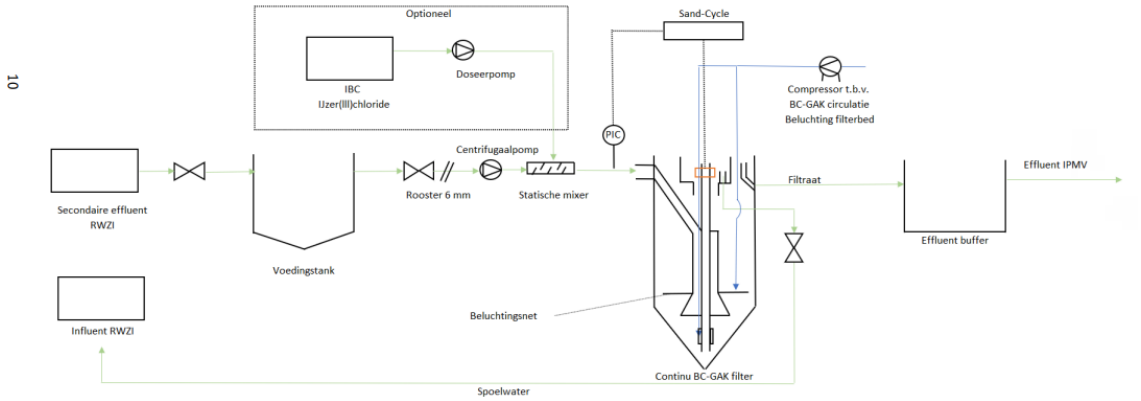
FIGURE 3.6 BLOCK DIAGRAM BODAC (BASED ON PILOT AT WWTP EMMEN)



The BODAC pilot (WWTP Emmen) consisted of two parallel (activated carbon) filtration steps with design residence times (EBCT) of 16 to 32 minutes. One filter contained already saturated GAC ('BODAC old'), while the other contained fresh GAC. Oxygen was dosed to the influent of both filtration steps to create aerobic conditions in the BODAC filters. This oxygen dosing is required to meet the oxygen demand during biological filtration. In biological activated carbon filtration, a biofilm develops on the activated carbon, allowing biological degradation (biodegradation) and adsorption of micropollutants to occur together. Through biodegradation, adsorbed micropollutants are broken down, which leads to bioregeneration of the activated carbon, thereby maintaining part of the GAC adsorption capacity. The expected advantage compared to the GAC reference is that less GAC is consumed.

CONTINUOUS BIO-GAC + AIR

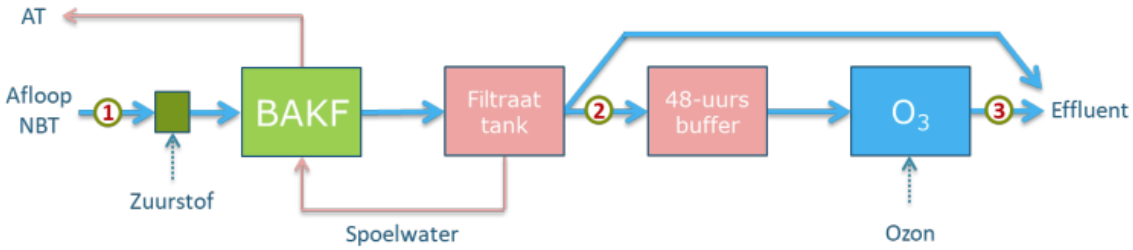
FIGURE 3.7 **BLOCK DIAGRAM BIO-GAC + AIR**



This technology concept, a combination of BODAC and upflow GAC, concerns a continuously operated upflow GAC filter which is actively aerated. As in the BODAC concept, adsorption and biological degradation on and around the filtration medium go hand in hand. In the pilot, the concept of continuous filtration with a fresh GAC filter filling was investigated for the removal of micropollutants. Aerating the filter promoted the growth of bacteria capable of micropollutant degradation. This extended the service life of the carbon, which is an expected advantage of the technology. Before the effluent enters the reactor, it undergoes pretreatment with a drum screen (as in BODAC).

AUREA (BO_3)

FIGURE 3.8 BLOCK DIAGRAM AUREA (BO_3) PILOT INSTALLATION, NUMBERS 1-3 INDICATE SAMPLING POINTS



The 48-hour buffer in Figure 3.8 relates only to the pilot installation and does not form part of a full-scale installation.

The Aurea technology is a two-step process made up of, respectively, biological activated carbon filtration (BACF) and ozonation for enhanced removal of micropollutants and reduced ecotoxicity. In the first step, the BACF, organic components are (partially) biodegraded under aerobic conditions. This includes the (partial) breakdown of DOC as well as degradation of a selection of pharmaceutical residues. Because of this degradation, a low ozone dose in the second step is sufficient to oxidise bio-recalcitrant components. In addition to a reduced CO_2 footprint, this lower-dose ozonation entails a much lower risk of bromate formation (expected advantage). Furthermore, it is expected that by combining several removal processes, a broader palette of micropollutants can be removed compared to BACF alone (however, the pilot has shown that this range is not broader than with ozonation alone, see also appendix 6).

3.4.3 COMPARISON

GAC, NON-AERATED

The table below summarises the main characteristics of the non-aerated GAC technologies, including a comparison with the GAC reference. O3-STEP is a combined technology in which a GAC filter is preceded by ozonation. In terms of treatment efficiency, for all technologies a minimum removal of 80% for 7/11 indicator substances is assumed over the entire WWTP.

The GAC reference and the O3-STEP pilot were implemented at WWTP Horstermeer, whereas both upflow GAC pilots were implemented at WWTP Hapert. What stands out is that the GAC reference consumes much more GAC on an annual basis than the other GAC technologies — more than double. This difference is due to the way the GAC reference was calculated (with an EBCT of 30 minutes and a service life of months) and the performances in the pilots. Another noteworthy observation is that CarboPlus utilises a much smaller GAC grain size and has a much smaller filter volume compared to the other technologies. Nonetheless, on an annual basis, GAC consumption in the CarboPlus system is equal to that of the DynaCarbon filter. An important distinction between the CarboPlus system and the other GAC filters is that in CarboPlus fresh GAC is continuously dosed. This offers opportunities for optimisation in periods when removal in the biological stage is higher or lower, since in those cases less or more carbon could be dosed.

In calculating removal efficiencies for non-aerated GAC filters, it was assumed that several filters operated in parallel and that the fillings were replaced independently of one another. This resulted in an average removal efficiency across the different filters.

Finally, the O3-STEP system had the lowest annual GAC consumption as well as low ozone dosage. Moreover, this system offers the possibility to also effectively remove N (NO_3) and P through the addition of metal salts and methanol to the filter. For O3-STEP, it should also be noted that the assumed service life of >35,000 bed volumes could turn out to be higher in actual practice. As with aerated GAC filters, bioregeneration may occur in the O3-STEP system without N and P removal, but this requires further investigation in practice.

TABLE 3.5 SPECIFIC DESIGN ASSUMPTIONS FOR ADSORPTION ONTO GRANULAR ACTIVATED CARBON (NON-AERATED)

	Unit	GAC reference	O3-STEP	Upflow GAC CarboPlus	Upflow GAC DynaCarbon
Pilot	WWTP	Horstermeer	Horstermeer	Hapert	Hapert
Type filter	-	Downflow	Downflow	Upflow	Upflow
Type GAC	-	GAC 612 WFD	GAC 612 WFD	Cyclecarb 305, Chemviron [1]	Cyclecarb 401, Chemviron
EBCT at average flow	min	17	17	10	28
Treated flow	%	80	70	80	80
GAC service life	bed volumes	<10,000	>35,000	- [2]	15,000
GAC dosage	mg/l			30	
O_3 dosage	g O_3/g DOC	-	0.4 [3]	-	-
$FeCl_3$	mol Fe_{3+}/mol P		0 – 4 [3]		
Methanol (99.8%)	kg/d		... [3], 225 [4]		
Sludge production[5]	g/m^3	-	-	-	-
Energy consumption	kWh/m^3		0.12 – 0.13 [3]	0.048	0.108
Removal efficiency 7/11 WWTP	%	80-85	80-85	80-85	80-85
Nutrient removal	-	-	N+P [4]	-	-

[1] Micro grains.

[2] Continuous addition of fresh GAC.

[3] Without and with $FeCl_3$ and methanol dosing.

[4] 4 g methanol/g NOx-N +1.2 g methanol/g O_2.

[5] Sludge production based on biological growth. The capture of suspended solids is dependent on the concentration of undissolved constituents in the effluent and has not been included in sludge production.

GAC, AERATED (BACF)

The table below provides a summary of the main characteristics of the aerated GAC technologies, including a comparison with the GAC reference. Aerated GAC filters operate according to the principle of biological activated carbon filtration (BACF), in which the biomass surrounding the GAC degrades micropollutants. There is an interaction between micropollutant adsorption onto the GAC and biological degradation of the adsorbed pollutants by the biofilm that is present. As a result, the adsorption capacity of the GAC is maintained (bioregeneration). The BODAC and Aurea pilots were carried out with saturated GAC that had been in use for 13 years at the ultrapure water plant in Emmen. The aerated continuous Bio-GAC pilot was operated with fresh GAC and ran for about 1.5 years. Despite this shorter running time, it can be argued that for Bio-GAC, too, the replacement frequency is likely to be 15 years, since like BODAC and Aurea, it is an aerated GAC filter. The sensitivity analysis (section 4.1.4) explores the effect of varying the assumed service life for Bio-GAC.

From Table 3.6 it can be observed that the treated flow ranged from 70% to 80% of the total flow of the WWTP. For BODAC, it would seem logical to also treat 80% of the total flow, because the required 80% removal efficiency for 7/11 indicator substances can then be more easily achieved. Another point to note is that the three aerated GAC filters are operated at a relatively high oxygen concentration, of >20 mg/l. The grain size of the GAC reference is somewhat larger than that in the BACF systems. It is also notable that the filter volumes are of the same order of magnitude, between 400 and 520 m^3. At nominal flow,

this results in a contact time (EBCT) of more than 30 minutes. Furthermore, the three BACF systems have a relatively long service life compared to the GAC reference. Specifically, the service life of the BACF systems is 30 times longer than that of the GAC reference. For the GAC in the BACF systems, a service life of 15 years was assumed, but this may be even longer in real-world practice (this still needs to be demonstrated). Because of this long service life, the replacement costs for GAC are significantly lower in this technology, and the CO_2 footprint is improved.

It is important to note that, based on the pilot results, the assumption is made that BACF does not require pre-filtration and that a service life of 15 years is achievable. However, in practice, this remains to be demonstrated for different types of effluent. At WWTP Horstermeer, BACF was operating without pre-filtration, but at WWTP Emmen (BODAC and Bio-GAC), pretreatment was found to be required, for example, using a drum screen, to prevent excessive material from entering and clogging the filter. For this reason, at WWTP Aartselaar (Aquafin) these filters were installed as a pre-treatment step in the full-scale facility (O_3 + GAC). The need for pre-filtration and the service life of the GAC therefore remain uncertainties and topics for further research regarding BACF technology.

Another topic for research is the potential crushing and agglomeration of the GAC grains in the filter.

TABLE 3.6 SPECIFIC DESIGN ASSUMPTIONS FOR ADSORPTION ONTO GRANULAR ACTIVATED CARBON (AERATED) FOR A 100,000 PE WWTP

	Unit	GAC reference	BODAC	Continuous Bio-	Aurea (B03)
Pilot	WWTP	Horstermeer + experiences in Switzerland	Emmen	Emmen	Horstermeer
Type filter	-	Downflow	Aerated, downflow	Aerated upflow	Aerated, downflow
Type GAC	-	GAC 612 WFD	Norit 830P	Norit GAC 830 AF	Norit 830P
Treated flow	%	80	70	80	70
Aeration	mg O_2/l	No	20 [1]	28	20 [1]
EBCT at average flow	min	17	23	37	30
GAC service life	Months	6	180	24 – 180 [3]	180
GAC consumption	Ton/year	395 [2]	12 [2]	13 [2]	16
O_3 dosage	g O_3/g DOC	-			0.3
$FeCl_3$	mol Fe_{3+}/mol P			0 – 4 [4]	
Sludge production	Ton/year	-	12	14 – 220 [4]	16
Energy consumption	kWh/m^3	0.12-0.13	0.14	0.073	0.084
Removal mechanism	-	Adsorption	Adsorption + biological degradation	Adsorption + biological degradation	Adsorption + biological degradation
Removal efficiency 7/11 WWTP	%	80-85	80	80	85
Nutrient removal	-	-	NH_4	NH_4 (+ P) [4]	NH_4

[1] Pure oxygen.

[2] Assuming 100,000 PE WWTP scale, 15-year service life for BACF technologies and GAC bulk density of 450 kg/m^3.

[3] Continuous Bio-GAC was started up 2 years ago with fresh GAC. An equivalent service life to BODAC and Aurea is realistic given the process similarities.

[4] Without and with $FeCl_3$ dosing for supplementary P removal, 100,000 PE WWTP scale.

3.5 ADSORPTION ONTO OTHER NON-FOSSIL MATERIALS

3.5.1 TECHNOLOGY CONCEPT AND OPTIMISATIONS

As indicated earlier, binding or adsorption of micropollutants onto activated carbon is already being applied at operational scale, mainly abroad, but to some extent in the Netherlands as well. Removal efficiencies are high, the costs are relatively low. However, the activated

carbon used is typically of fossil origin (derived from coal or lignite). The challenge is to produce activated carbon more sustainably (with a lower CO_2 footprint), or to replace it with alternative adsorbents, such as zeolite or cyclodextrins.

Within the IPMV, a market survey and laboratory tests were carried out on the availability and quality of non-fossil PAC (STOWA 2020-19 and 2021-24). These concluded that non-fossil PAC is commercially available and achieves removal efficiencies comparable to those of fossil PAC. Furthermore, these alternatives have been tested in practice in the PACAS Nereda study and at WWTP Groesbeek.

For GAC applications at WWTPs, however, non-fossil GAC is hardly available, since the hard carbons required for GAC are more readily obtained from coal or lignite. The advantage of GAC over PAC is that saturated GAC can be effectively regenerated, which results in a substantially lower CO_2 footprint and a lower cost profile compared to the use of fresh GAC. During regeneration, a small fraction of the GAC is lost, which must be replenished with fresh GAC.

Within the IPMV, adsorption of micropollutants onto other non-fossil materials (i.e., other than activated carbon) was explored in pilot studies on cyclodextrins and high-silica zeolites. The performance of two technologies was compared with that of GAC filters:

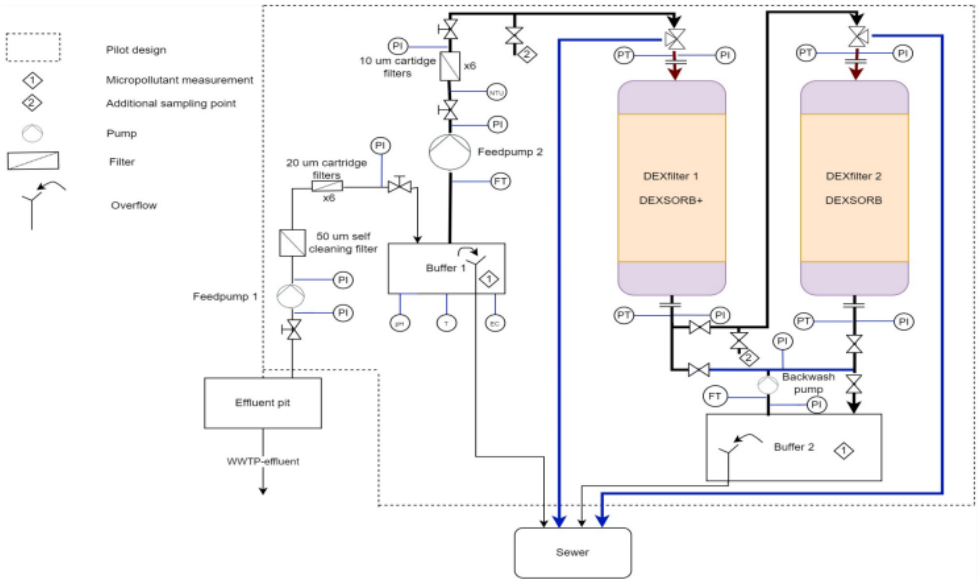
- DEX filter (cyclodextrins)
- AdOx (high-silica zeolites)

A more extensive description of these technologies is presented in the factsheets in appendix 5. A summary of each is provided below.

3.5.2 OVERVIEW OF INNOVATIVE TECHNOLOGIES

DEX FILTER

FIGURE 3.9 BLOCK DIAGRAM DEX FILTER (BASED ON PILOT AT WWTP LELYSTAD)

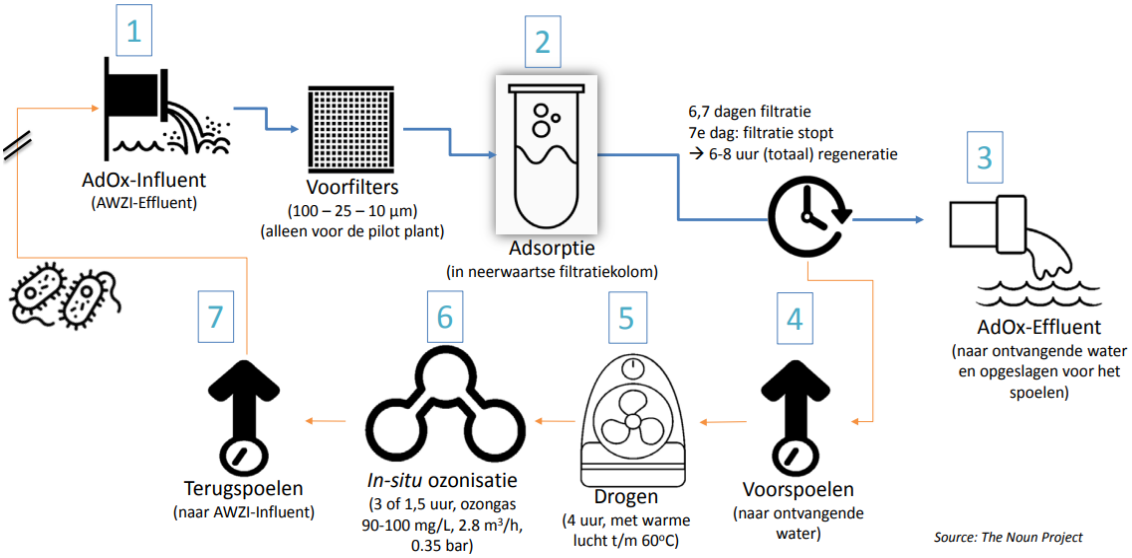


DEXSORB is the trade name for cyclodextrins produced by CycloPure for application in water treatment. Originally developed for the air freshener industry, cyclodextrins are ring-shaped molecules composed of sugars. They form cup-like structures with a positive or negative charge, onto which micropollutants can adsorb through a combination of electrostatic and hydrophobic interactions, as well as a size-exclusion mechanism.

The expected advantage of this technology is a reduced CO_2 footprint, because the adsorbent can be regenerated on-site with methanol, at room temperature.

ADOX

FIGURE 3.10 BLOCK DIAGRAM ADOX (BASED ON PILOT AT WWTP LEIDEN-NOORD)



AdOx is an adsorption-oxidation process for removing organic micropollutants. It uses granular high-silica zeolites in a downflow fixed-bed reactor, where micropollutants are adsorbed from the wastewater. Once the adsorption column is saturated, it is regenerated in-situ with ozone gas. This process provides selective removal of micropollutants; natural organic matter (NOM) is not adsorbed. The combination of adsorption on zeolites with in-situ regeneration using ozone offers several potential advantages: no formation of by-products such as bromate in the treated WWTP effluent (since ozone is not dosed into the main stream), minimal transport movements (due to in-situ regeneration), and low ozone consumption, since NOM does not adsorb to the zeolite. Ozone consumption is therefore lower compared to conventional technologies in which ozone is introduced directly into the wastewater.

3.5.3 COMPARISON

DEX filter and AdOx are two very different technologies. Nevertheless, they are shown side by side in the table below. The table indicates that AdOx material is regenerated more frequently, via in-situ ozonation. The DEX filter is regenerated with methanol, with the adsorbed pollutants ending up the methanol. External treatment of the methanol remains to be further developed in a follow-up phase.

The design basis of AdOx is treatment of 70% of the WWTP effluent, while the DEX filter treats 80% of the effluent. It is also worth noting that the DEX filter removes some of the N and P present, which could offer synergies with Water Framework Directive objectives. Further research is needed to determine to what extent cyclodextrins are capable of additional N and P removal.

Regarding both technologies, outstanding research questions remain that will need to be addressed before application at full WWTP scale is possible. For the DEX filter, regeneration of the cyclodextrins and further processing of the methanol are key issues, while for AdOx, improved zeolites are under development, aimed at achieving higher micropollutant removal efficiencies. For both technologies, potential pre-treatment requirements still have to be assessed. Also for both technologies, longer periods of pilot testing are needed to make refinements and optimisations and test the results of these adjustments. In the long term (>5 years), both technologies show strong potential as alternatives to ozonation or activated carbon.

TABLE 3.7 **SPECIFIC DESIGN ASSUMPTIONS FOR OTHER ADSORPTION TECHNOLOGIES, 100,000 PE WWTP**

	Unit	DEX-filter	AdOx
Pilot	WWTP	Lelystad	Leiden-Noord
Type filter	-	Self-cleaning filter and cartridge filter	Pre-filter
Type of adsorbent material	-	Cyclodextrins	Zeolite granules
Treated flow	%	80	70
Grain size (diameter)	mm	0.2 – 1.5	2-15
Filter volume	m^3	174	174
Service life of media until regeneration	time	6.8 months	7 days
O_3 dosage per m^3 treated effluent	kg/m^3		0.0077
Energy consumption per treated m^3	kWh/m^3	0.03	0.06
Removal efficiency 7/11 incl. WWTP	%	80-95	79
Nutrient removal	-	N, P	-

3.6 OXIDATIVE TECHNOLOGIES

3.6.1 TECHNOLOGY CONCEPT AND OPTIMISATIONS

There is a wide range of so-called oxidative treatment technologies with which micropollutants in WWTP influents can be degraded. Unlike adsorption and filtration technologies, in which pollutants remain intact, oxidative processes break them down.

This breakdown usually does not result in full mineralization to CO_2. Typically, organic micropollutants are oxidised into so-called transformation products. In almost all cases, these substances are no more or less toxic than the micropollutants from which they are formed. With just a few exceptions, transformation products are therefore not classified as undesirable (STOWA, 2022). To better understand toxicity, bioassays can be used, as described in the sections on ecotoxicological risk (paragraph 2.8 and 4.2.1).

In addition breaking down organic micropollutants, ozone (or another oxidant) also reacts with other organic and inorganic components in the WWTP effluent (the matrix), forming so-called oxidation products. The term 'oxidation products' thus refers to the total of transformation products and oxidation by-products. In theory, thousands of different oxidation products can be formed during ozonation, many of which are unknown. Among the known oxidation products, some are undesired. These are substances that could potentially be formed at ecotoxicologically relevant levels and/or pose risks to human health by adversely affecting drinking water resources. Most undesired organic oxidation products are readily biodegradable; examples of these are aldehydes, ketones and carboxylic acids. Some undesired inorganic by-products are difficult to remove, such as bromate.

Ozonation (dosing of O_3) is the most commonly applied oxidative technology, especially outside the Netherlands. Within the Netherlands, the first full-scale installation came into operation in 2021 at WWTP Houten. Ozonation systems were later installed at WWTPs Wervershoof (from 2024) and Hapert[1] (from late 2024). Combined technologies were being installed or in operation at WWTP Horstermeer (where ozonation was installed in 2024 upstream of an existing GAC filter), at WWTP Dinther (where a PACAS-ozone demonstration system was installed in summer 2024) and at WWTP Winterswijk (where an ozonation + GAC system was installed in late 2024).

Beyond ozonation, other technologies can be applied for the transformation, such as ultraviolet (UV) light in combination with hydrogen peroxide (H_2O_2).

Within the IPMV, various optimisations of oxidative and/or ozonation technologies were investigated:

- SF + UV/H_2O_2
- O_3 + ultrasound
- O3-STEP (without N and P removal) (combination of oxidation and activated carbon)
- PAC + O_3 (combination of oxidation and activated carbon)
- MicroForce (combination of oxidation and biological degradation)
- Aurea (BO_3) (combination of oxidation and biological degradation)
- Direct nanofiltration (NF) + UV/H_2O_2 (combination of oxidation and filtration)
- O_3 + ceramic microfiltration (MF) (combination of oxidation and filtration)

1 The design already takes into account the dosage of hydrogen peroxide.

Key questions within this theme are whether there are (combinations of) cost-effective oxidative technologies that significantly reduce the risk of harmful by-products formation compared to current practices, and how can formation of harmful by-products be minimised. An example is the conversion of bromide into the persistent compound bromate during ozonation. Within the IPMV, a literature review was conducted on oxidation products. This led to development of a technical handbook on oxidation products in ozonation and how these can be prevented/minimised. These two publications are listed in appendix 1 and not further elaborated on in this evaluation.

Within the IPMV, optimisations of ozonation technologies focused mainly on lowering the specific ozone dosage (g O_3/g DOC). The technical handbook on oxidation products in ozonation (STOWA 2022-48) reached the following conclusions regarding the specific ozone dosage:

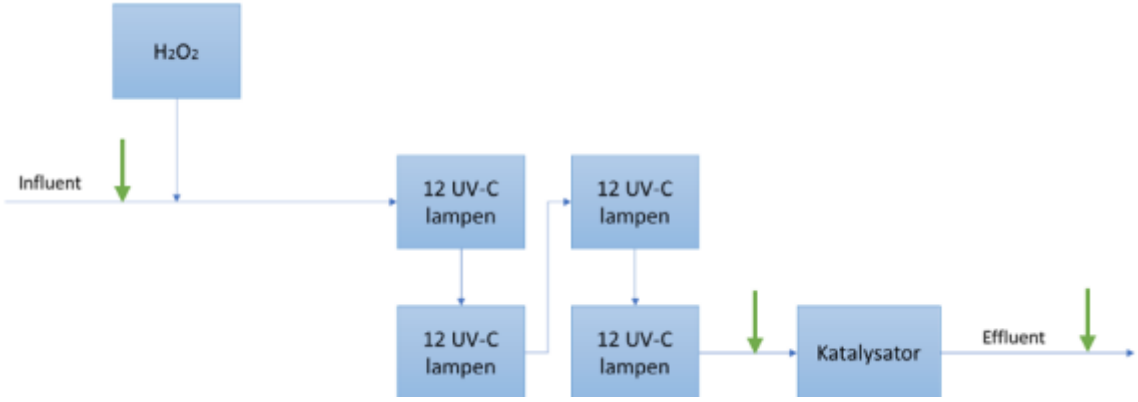
- A relative ozone dosage of <0.6 g O_3/g DOC is sufficient for >80% removal of 7/11 indicator substances.
- Little to no bromate or N-nitrosodimethylamine (NDMA) formation occurs at an ozone dosage of <0.6 g O_3/g DOC.
- Biological effect measurements show improvement across (almost) all toxicological endpoints at dosages of <0.6 g O_3/g DOC, although the P53-Calux bioassay may show a slight negative effect.

The factsheets in appendix 5 present details on the above oxidative technologies investigated within the IPMV. The sections below describe and compare them in more summarised form.

3.6.2 OVERVIEW OF INNOVATIVE TECHNOLOGIES

SF+UV/H_2O_2

FIGURE 3.11 BLOCK DIAGRAM SF+UV/H_2O_2 (BASED ON PILOT AT WWTP AARLE-RIXTEL)



In the oxidative technology combining UV light with hydrogen peroxide (H_2O_2), H_2O_2 is first dosed in excess and then irradiated with UV light (wavelength 254 nm). This irradiation of H_2O_2 produces hydroxyl radicals. Because not all of the H_2O_2 is consumed in the treatment process, the water is passed through a catalyst bed to prevent the residual H_2O_2 from being discharged into surface water with the effluent. In the catalyst bed, the remaining H_2O_2 is converted into H_2O and O_2. The treated water is then discharged into the effluent channel of the WWTP. Three reactions occur in this process, namely, (1) photolysis, (2) oxidation with hydroxyl radicals and (3) oxidation with H_2O_2. This combination of reactions offers several advantages: some pharmaceuticals are broken down primarily by photolysis, while

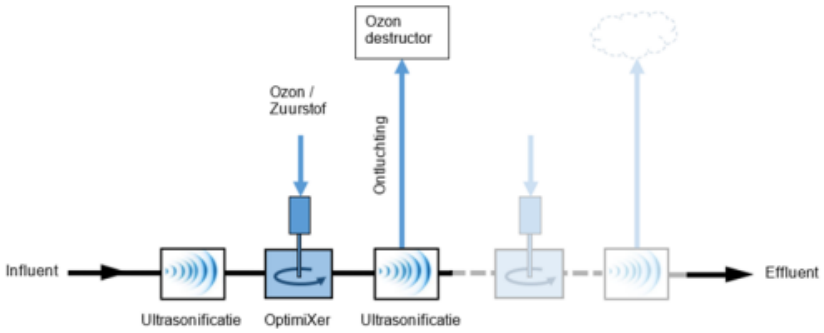
others are hardly affected by photolysis but converted mainly through oxidation. The combination of UV and H_2O_2 was tested at WWTP Aarle-Rixtel.

Expected advantages of this technology compared to the reference case are increased removal efficiency and an improved SIMONI score (Smart Integral Monitoring, an indicator of toxicity).

During the pilot study, the transmittance of the effluent from the Aarle-Rixtel WWTP was low (40%), meaning the measured removal efficiency did not meet the 80% removal efficiency required for the IPMV evaluation. Pretreatment can increase UV transmittance. Therefore, this report is based on the results from the, albeit more indicative, follow-up study using sand filtration.

O_3 + ULTRASOUND

FIGURE 3.12 BLOCK DIAGRAM O_3 + ULTRASOUND



In O_3 + ultrasound (USONiQ) a combination of ozonation and ultrasound is applied. Ultrasound enhances the ozonation process in several ways:

- Breaking up bacterial clusters.
- Disrupting chemical bonds in cell membranes.
- Improving the formation of free radicals from ozone.
- Improving ozone transfer from the gas to the liquid phase.

The system consists of a stainless steel, tube-shaped reactor. In the reactor, a sequence of processes are applied: ultrasound, ozone and then ultrasound again. Ultrasound generators are distributed along the pipe in the sections serving as the reaction chamber for ultrasound treatment. In the ozonation section, ozone is added close to a patented mixing disk that ensures optimal mixing of the introduced ozone.

Expected advantages over the ozonation reference are two. First, the spatial footprint of a USONiQ unit is significantly smaller than that of a conventional ozonation unit. Second, for O_3 + ultrasound, considerably shorter contact times and lower O_3 doses are sufficient to achieve the same removal efficiency as with conventional ozonation systems.

O3-STEP (WITHOUT N AND P REMOVAL) (COMBINATION OF OXIDATION AND ACTIVATED CARBON)

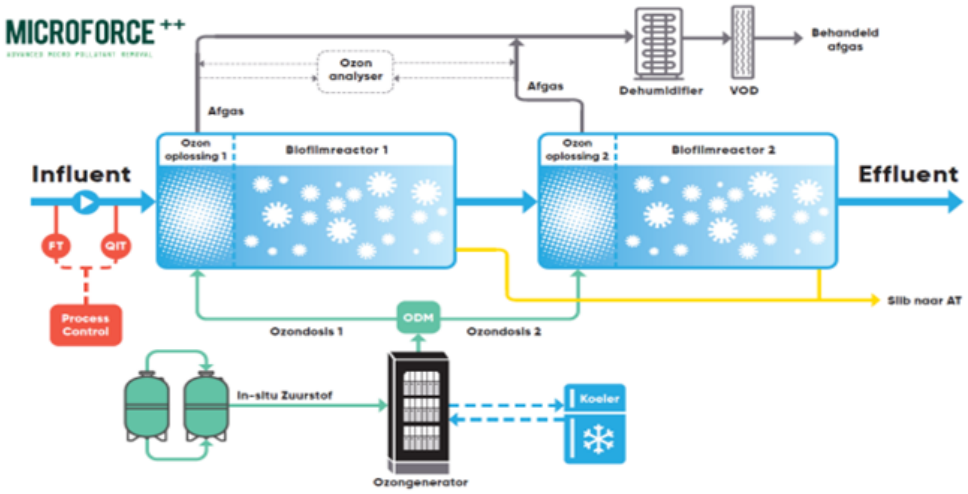
Because this technology is a combination of oxidation and granular carbon, it was discussed earlier, in section 3.4.

PAC + O_3 (COMBINATION OF OXIDATION AND ACTIVATED CARBON)

Because this technology is a combination of powdered carbon and oxidation, it was discussed earlier, in section 3.3.2.

MICROFORCE (COMBINATION OF OXIDATION AND BIOLOGICAL DEGRADATION)

FIGURE 3.13 BLOCK DIAGRAM MICROFORCE++



MicroForce++ consists of ozonation and biological oxidation. The MicroForce++ process is made up of two consecutive O_3/bio-reactors arranged in series, each operated with a specific ozone dose. In each reactor, the effluent is first treated with ozone in the ozonation compartment, followed by a biological reactor with a biofilm-on-carrier technology where further degradation takes place.

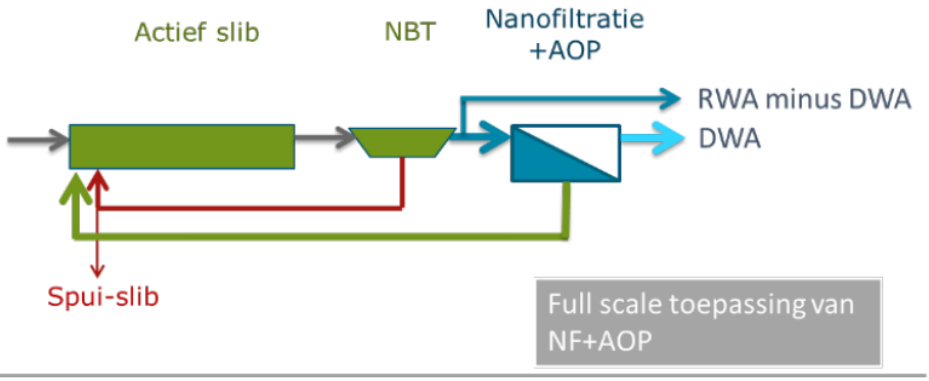
The expected advantage of this technology is that the addition of a biological step reduces ozone demand compared to current practice. In addition, the combination of ozonation and biological treatment enables extensive conversion of ammonium.

AUREA (BO_3) (COMBINATION OF OXIDATION AND BIOLOGICAL DEGRADATION)

Because this technology is a combination of biological activated carbon filtration and oxidation, it was discussed earlier, in section 3.4.2.

DIRECT NANOFILTRATION AND UV/PEROXIDE (COMBINATION OF OXIDATION AND FILTRATION)

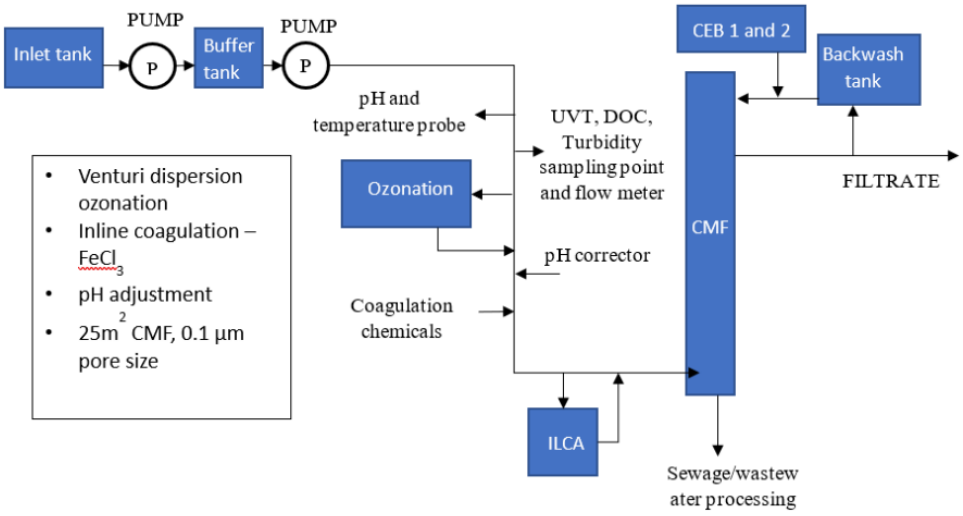
FIGURE 3.14 **BLOCK DIAGRAM DIRECT NANOFILTRATION AND UV/PEROXIDE**



Nanofiltration (NF) is a separation technique. NF membranes are physical barriers with pore sizes in the range of 1 to 10 nm. Pathogens and suspended solids can therefore be almost completely removed from water. Larger, dissolved molecules are also almost completely removed, including humic acids and a portion of the micropollutants, as well as phosphate and nitrate. Ammonium is a small molecule and is not removed. The separated components end up in a concentrate stream, which can be further treated if required. Compared with the reference technologies, NF has a considerable co-benefit (expected advantage): because the membrane serves as an absolute barrier, for example, microplastics are retained and disinfection occurs. To increase removal efficiency, the NF step is followed by post-treatment with UV and hydrogen peroxide. Because the membranes remove 'colour components', UV transmittance of the water is significantly increased, meaning that treatment with UV light can be efficiently applied. In addition, this hybrid treatment offers greater robustness in delivering bacteriologically and chemically reliable water at a quality level approaching that of drinking water. This opens up possibilities for high-value reuse.

O_3 + CERAMIC MICROFILTRATION (COMBINATION OF OXIDATION AND FILTRATION)

FIGURE 3.15 **BLOCK DIAGRAM OZONATION AND CERAMIC MICROFILTRATION**



In ozonation with ceramic microfiltration (MF), water is first treated through ozonation to remove micropollutants. Depending on the desired effluent quality, this step can be combined with H_2O_2 dosing. This is followed by an in-line coagulation (ILCA) step for optimised ceramic microfiltration (CMF) to remove suspended particles, microplastics and bacteria/viruses. The expected advantage of this technology is that the water produced is of suitable quality for high-value effluent reuse.

COMPARISON

Table 3.8 presents the design assumptions for the oxidation component of the technologies. It shows that all the technologies apply specific ozone dosages ranging from 0.3 to 0.55 g O_3/g DOC. Therefore, they are all lower than the ozonation reference, with its dosage of 0.6 g O_3/g DOC.

The residence time in the contact tank is also generally shorter, ranging from just a few minutes to 15 minutes. This translates to lower ozone usage and a more compact reactor volume. Only for MicroForce is the residence time longer than that of the reference, as each of its two reactors has a residence time of 15 minutes. However, because each reactor consists of an ozonation stage combined with a biological stage, these values are not directly comparable. Two technologies (O_3 + ultrasound and MicroForce) have their own system for adding ozone; the other technologies can be fitted with any type of introduction system (diffusers are referenced in the table).

Regarding energy consumption, SF + UV/H_2O_2 is by far the highest, at approximately 0.95 kWh/m^3, due to the energy demand of the UV lamps. Because of low light transmission in the pilot, more UV lamps were required than originally expected. The energy consumption of PAC + O_3, at 0.15 kWh/m^3, is slightly higher than the ozonation reference (0.13 kWh/m^3 treated flow), while for the other technologies it is 0.10 and 0.13 kWh/m^3 treated flow, making them slightly lower than or similar to the reference.

TABLE 3.8 SPECIFIC DESIGN ASSUMPTIONS FOR OXIDATIVE TECHNOLOGIES (OXIDATION COMPONENT)

Parameter	Unit	O_3 ref	O3-STEP	SF + UV/H_2O_2	O_3 + Ultrasound	PAC+O_3	MicroForce	Aurea (BO_3)	NF + UV/H_2O_2	O_3 + ceramic MF
Oxidation with ozone and/or H_2O_2										
Nominal O_3 dosage	g O_3/g DOC	0.6	0.4	-	0.55	0.5	0.43[2]	0.3	-	0.6
Contact time O_3 reactor	min	20	10	-	a few minutes	15	2x 15[3]	7.5	-	20
O_3 introduction[1]	-	diffusers	diffusers	-	USONiQ system	diffusers	PureBlue system	diffusers	-	diffusers
H_2O_2	ppm	0	0	30	0	0	0	0	15	0
UV technologies										
Number of UV lamps	number/1,000,000 m^3 treated			156					18	
HRT UV	min			6					n.d.	
Dosage range	J/m^2			15.000					6.100	
Transmittance	%			60					95	
Energy consumption[4]										
Total	kWh/ m^3 treated	0.13	0.12	0.95	0.13	0.15	0.11	0.08	0.39	0.20
Technology excl. pumping and backwash water	kWh/ m^3 treated	0.096	0.078	0.092	0.097	0.110	0.068	0.047	0.39	0.146
Pumping 8 m pumping head	kWh/ m^3 treated	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0	0.035
Backwash water	kWh/ m^3 treated	0	0.002	0.020	0	0	0.002	0.002	0	0.020

[1] If diffusers; other introduction systems are also possible. Though in research venturi systems have been used, for full-scale installations diffusers are generally recommended.

[2] Total dosage is divided over two sequential reactors.

[3] Two bioreactors with a residence time of 15 min each (ozonation + biological stage).

[4] Energy consumption of ozonation may be somewhat lower in practice. This remains to be established by measurements at full-scale ozonation installations.

The following sections provide design assumptions for the 'other' removal mechanism in the technologies combined with oxidation; respectively, activated carbon, biological degradation and filtration.

COMBINATION OF OXIDATION AND ACTIVATED CARBON

Combining an activated carbon technology with oxidation results not only in a lower required ozone dosage (see above), but also lower PAC consumption or a longer GAC service life compared to the PACAS and GAC reference technologies (Table 3.9).

TABLE 3.9 SPECIFIC DESIGN ASSUMPTIONS FOR OXIDATIVE TECHNOLOGIES (WITH ACTIVATED CARBON), 100,000 PE WWTP

Parameter	Unit	PACAS ref	O_3 ref	GAC ref	O3-STEP	PAC+O_3
PACAS	0				0	
Nominal PAC dosage	mg/l	20	-	-	-	7.5
Fresh PAC consumption[2]	t PAC/year	123	-	-	-	46.0
DS in dewatered sludge without PAC (and possibly additional Fe)	%DS	-	21.1	21.1	21.1	-
DS in dewatered sludge with PAC (and possibly additional Fe)	%DS	22.1	-	-	-	21.6
Additional sludge to be removed[1]	kg DS/m^3 treated	0.016	-	-	-	0.006
Granular activated carbon (GAC)						
Hydraulic loading	m/h			8	10 to 15	
EBCT at DWF design peak	min			30	10	
Carbon service life	Months			4-6	23	
Carbon service life	bed volumes				>35.000	
Fresh GAC consumption[2]	t GAC/year			83.2	31.2	
Regenerated GAC consumption[2]	t GAC/year			312	49.6	
Additional sludge to be removed	kg DS/m^3 treated			0	0	
Backwash water	% of influent flow			1%	1%	

[1] The treated flow used to calculate sludge removal for both PACAS and PAC + O_3 is 80% x 7,665,000 m^3/year.

[2] PAC and GAC consumption calculated for a standard 100,000 PE WWTP at 150 g COD (chemical oxygen demand).

COMBINATION OF OXIDATION AND BIOLOGICAL DEGRADATION

Two technologies, MicroForce and Aurea (BO_3), combine ozonation with biological degradation. Table 3.10 compares the design of the biological step of both technologies.

TABLE 3.10 SPECIFIC DESIGN ASSUMPTIONS FOR OXIDATIVE TECHNOLOGIES (OXIDATION COMPONENT)

Parameter	Unit	MicroForce	Aurea (BO_3)
Biological reactor in combination with O_3			
Carrier material type	-	HDPE rings Ø 17 mm, thickness 5 mm, specific surface area 1,150 m^2/m^3	GAC
Carrier material service life	months	1	180
Carrier material density	kg/m^3	n.d.	400 – 500
Biological reactor contact time	min	2 reactors each with 7.5–15	20 – 35
Biological reactor height	m	2.2 – 3.5	2 – 3.5
EBCT minimum	min	3.75	20
EBCT nominal	min	15	30
Oxygen setpoint ramp-up	mg/l	n.d.	0 – 20
Sludge produced	kg DS/m^3 treated	0.0030	0.0030

[1] For Microforce, carrier replacement would not be required. For Aurea (BO_3), the service life is set as equal to BODAC, at 15 years (see section 3.4).

COMBINATION OF OXIDATION AND MEMBRANE FILTRATION

A comparison of the two technologies that combine oxidation and filtration is presented in section 3.7.3.

3.7 FILTRATION TECHNOLOGIES IN COMBINATION WITH OXIDATION

3.7.1 TECHNOLOGY CONCEPT AND OPTIMISATIONS

Filtration technologies remove micropollutants from WWTP effluent based on molecular size. They are widely applied in the drinking water and industrial sectors, but internationally there has as yet been little experience with their use in post-treatment of WWTP effluent. Membrane filtration application is limited to situations where drinking water is scarce and there is a need to upgrade WWTP effluent to drinking water or process water quality. The two tested technologies are hybrid processes made up of a filtration step and an oxidation step.

Nanofiltration (NF) has long been widely used in the production of drinking water. In NF, water is forced through a membrane with extremely small pores (between 1 and 10 nm). Nanofiltration of effluent shows strong potential for advanced micropollutant removal, achieving removals of 90% or more. One challenge, however, is treatment of the separated fraction (the concentrate stream), in which micropollutants accumulate. Furthermore, drinking water has a very different composition compared to treated wastewater, which means that the technology cannot be applied without supplementary measures.

In microfiltration (MF), only undissolved constituents are removed. The pore size is 0.1 to 10 µm. MF requires no pretreatment, but has the drawback that some constituents, for example, viruses, are only partly retained in the filter, and dissolved components, such as micropollutants, are not removed at all. This means it must always be combined with an additional treatment step.

The treated water produced is of very high quality, making it attractive for reuse in other applications.

Within the IPMV, two filtration technologies were investigated:

- Direct nanofiltration and UV/peroxide (NF+UV/H_2O_2)
- Ozonation and ceramic microfiltration (O_3 + ceramic MF)

A detailed description of these filtration technologies is presented in the factsheets in appendix 5. The technologies are presented and compared in summary form below.

3.7.2 OVERVIEW OF INNOVATIVE TECHNOLOGIES

DIRECT NANOFILTRATION AND UV/PEROXIDE

Because this technology is a combination of oxidation and filtration, it was discussed earlier, in section 3.6.2.

OZONATION WITH CERAMIC MICROFILTRATION

Because this technology is a combination of oxidation and filtration, it was discussed earlier, in section 3.6.2.

3.7.3 COMPARISON

The findings of the pilot studies indicate that membrane filtration needs to be combined with other technologies to effectively remove micropollutants from WWTP effluent. In the case of direct NF, pretreatment with coagulation is required to reduce the load on the membranes. Ceramic MF on its own hardy removes micropollutants, so ozonation is needed as a complementary step.

For direct NF + UV/H_2O_2, the concentrate treatment route has not yet to be developed and it is therefore not included in the calculations of CO_2 footprint or costs. Because treatment of the concentrate stream will significantly affect both the costs and the CO_2 footprint of the technology, follow-up research is required before it can be considered for full-scale application at a WWTP.

For O_3 + ceramic MF, the ceramic microfiltration hardly contributes to micropollutant removal. The system's added value is therefore limited. However, like NF + UV/H_2O_2, this technology does offer the potential for high-value reuse of effluent. Here, too, further research is needed to optimise the process before it can be applied at WWTP scale.

Table 3.11 presents the characteristics of the membrane filtration processes. For the characteristics of the required oxidation component, see section 3.6.2.

TABLE 3.11 SPECIFIC DESIGN ASSUMPTIONS FOR FILTRATION TECHNOLOGIES (FILTRATION + OXIDATION STEP)

Parameter	Unit	O_3 ref	NF+UV/H_2O_2	O_3+ceramicMF
Filtration				
Prefilter applied	-	No	Yes, cloth filter 200 µm	No
Other pretreatment		No	Coagulation	No
Membrane type			DNF 80	Ceramic microfilter
Membrane material			Modified PES	Ceramic
Effluent treated	%		70	70
Recovery	%		75	-
Filtration cycle (filtration/cleaning)	min/min		59/1	-
$FeCl_3$ (coagulant)	mg Fe^{3+}/L		n.a.	10
Cleaning agents	type		Sodium hydroxide, sodium hypochlorite, citric acid	Sodium hydroxide, sodium hypochlorite, hydrochloric acid, hydrogen peroxide
Amount of cleaning agents for standard 100,000 PE WWTP at 150 g COD	kg/year		NaOH 50%: 6,592, NaOCl 15%: 14,313, Citric acid 50%: 12,842	Sodium hydroxide 50%: 25,245; sodium hypochlorite 15%: 11,870; citric acid 36%: 2,980; hydrogen peroxide 50%: 7,824
Total energy consumption	kWh/ m^3 treated		0.39	0.20
Energy consumption for technology excl. pumping and backwash water	kWh/ m^3 treated		0.39	0.146
Pumping 8 m pumping head	kWh/ m^3 treated		-	0.035
Backwash water	kWh/ m^3 treated		-	0.020

4

PERFORMANCE OF THE TECHNOLOGIES

This chapter describes and explores the performance of the investigated technologies. Both quantitative and qualitative performance indicators are considered. The quantitative performance is explained first, particularly removal efficiencies, CO_2 footprint and cost. This is followed by the qualitative performance, focused on ecotoxicity and co-benefits. These co-benefits include nutrient removal, mitigation of bromate formation and co-removal of AMR, PFAS and microplastics, as well as the potential for effluent reuse.

4.1 QUANTITATIVE PERFORMANCE OF TECHNOLOGIES

4.1.1 REMOVAL EFFICIENCIES: NL 7/11 AND EU 6/12 INDICATOR SUBSTANCES

DUTCH INDICATOR SUBSTANCES: 7/11

For this evaluation, the design criteria for the technologies were set such that an overall removal efficiency of 80% could be achieved for 7/11 Dutch indicator substances across the entire WWTP.

The removal efficiencies in Table 4.1 show that most technologies did in fact achieve or exceed this 80% target. On the basis of the 7/11 criterion, therefore, very little differentiation can be made between the technologies. Only SF + UV/H_2O_2 and AdOx had lower removal performances, at around 75%. For SF + UV/H_2O_2, this was caused by the relatively low UV transmittance of the effluent, and for AdOx it was because the research had not yet been completed when the IPMV program ended at December 31rd 2023.

The removal efficiencies in the table reflect the findings from pilot studies carried out at one WWTP during, in most cases, a relatively short period of time. The reports of the individual pilots provide more information on the efficiencies achieved per substance and which of the 7 substances were removed most effectively (see appendix 1). In some of the pilot studies, the removal efficiency of the WWTP where the pilot was carried out was also investigated, but in most cases post-treatment removal efficiency was converted to an overall efficiency figure using the calculation tool in STOWA 2020-06. For the IPMV, that tool was filled in for the standard 100,000 PE WWTP at 150 g COD (see appendix 2).

In the coming years, several demonstration and full-scale installations will be commissioned. These should make more information available regarding the technologies removal efficiencies in relation to particular design criteria.

TABLE 4.1 REMOVAL EFFICIENCIES (%) DUTCH AND EU INDICATOR SUBSTANCES (INDICATIVE)

Removal mechanism and technology	Share treated relative to influent	Post-treatment efficiency[2] 7/11[1]	Post-treatment efficiency[2] 11	Overall annual efficiency[2] 7/11[1]	Post-treatment efficiency[2]	Overall annual efficiency[2]
Indicator substances		**NL**	**NL**	**NL**	**EU[6]**	**EU[6]**
Adsorption onto PAC						
PACAS reference	100	-	-	80-85	n.a.	75-85
PAC + cloth filtration	70	approx. 90	approx. 85	approx. 80	approx. 85	75-80
PACAS Nereda	100	-	approx. 75[3]	80-85 (84)	n.a.	75-85
PAC + O_3	100 (PAC) 70 (O_3)	90-95	85-90	approx. 85	85-90	approx. 80
Adsorption onto GAC						
GAC reference	70	approx. 90	n.a.	80-85	80-90	75-85
O3-STEP (without N and P removal)	70	Up to 95%	approx. 80	approx. 80	>80	approx. 80
Upflow GAC[3]	80	80-90	75-80	80-85	75-90	75-85
BODAC	70	>80	n.a.	approx. 80	75-85	70-80
Bio-GAC + air	80	80-85	70-75	approx. 80	75-85	75-80
Aurea (BO_3)	70	approx. 90	75-80	approx. 85	80-85	75-80
Adsorption onto other non-fossil materials						
DEX filter[4]	80	80-95	75-90	80-85	80-95	75-85
AdOx	70	approx. 80	approx. 65	approx. 75[5]	75-80	70-75
Oxidative technologies and filtration technologies						
Ozonation reference	70	approx. 90	75	80-85	80-90	75-85
SF + UV/H_2O_2	80	>90	approx. 90	75-80	80-85	approx. 75
O_3 + ultrasound	70	approx. 90	approx. 85	85-90	85-90	80-85
O3-STEP (without N and P removal)	70	Up to 95%	approx. 80	approx. 80	>80	approx. 80
PAC + O_3	100 (PAC) 70 (O_3)	90-95	85-90	approx. 85	85-90	approx. 80
MicroForce	80	approx. 85	approx. 75	approx. 80	approx. 80	75-80
Aurea (BO_3)	70	approx. 90	75-80	approx. 85	80-85	75-80
NF + UV/H_2O_2	70	approx. 95	approx. 85	85-90	90-95	approx. 85
O_3 + ceramic MF	70	approx. 85	n.d.	approx. 80	80-90	75-85

[2] Removal efficiency for at least 7/11 Dutch indicator substances: benzotriazole, carbamazepine, diclofenac, irbesartan, gabapentin, metoprolol, hydrochlorothiazide, 4- and 5-methylbenzotriazole, sotalol, trimethoprim and venlafaxine, in each 24- or 48-hour flow- or time-proportional sample, accounting for 24h residence time of the water in the WWTP. These 11 indicator substances were chosen to monitor the effectiveness of treatment technologies for advanced removal of micropollutants from WWTP wastewater and have no relation with the potential environmental impact of the substances.

[2] The overall efficiency was calculated as the removal in WWTP effluent (incl. bypass) relative to influent. This calculations were based on 40% removal for the 7/11 indicator substances in the activated sludge process itself. Post-treatment efficiency is the efficiency of the technology itself, i.e. influent versus effluent to and from the pilot installation.

[3] Relative to WWTP influent.

[4] Average efficiency of non-aerated upflow GAC filters is higher than suggested by the pilot results due to the assumption of series operation and routine filter replacement. See also explanation in section 4.4.3. The same reasoning was applied for the DEX filter.

[5] Assumed baseline was 70% for 100,000 PE WWTP. If a larger fraction is treated, the overall efficiency will also be higher. Research on this technology is still under way.

[6] Reference technology efficiencies are based on the proposed text drafted for the IPMV regarding the EU Directive and considering measurement data for PACAS in Papendrecht (STOWA 2018-02). Efficiencies for the pilots are indicative (some calculated, others inferred). Annual efficiency in this table is not the same as the minimum efficiency in every sample, as now foreseen in the EU Directive.

DUTCH INDICATOR SUBSTANCES: EFFECT OF COMBINED TECHNOLOGIES

Appendix 6 presents a comparison of the different stand-alone and combined technologies. From this comparison, a number of observations can be made:

- Looking at the ozonation reference and the PACAS reference, differences can be seen in removals of the individual substances. Some are removed more effectively with PACAS, while others are removed better with ozonation.
- PAC + O_3 was compared with the ozonation reference and the PACAS reference at a similar removal efficiency of 80-85% for 7/11 indicator substances over the entire WWTP. This indicates that:
  - The substances which are usually removed more effectively by PAC, and less effectively by ozonation, were better removed by the combined technology compared to ozonation alone. However, for the individual substances, removal efficiencies of PAC + O_3 are not necessarily higher than those with PACAS alone.
  - The reverse also applies: the substances that are usually removed more effectively by ozonation, and less effectively by PAC, were better removed by the combined technology than with PACAS alone.
- In the BODAC pilot, both new and old GAC were investigated. With new GAC, the primary removal mechanism is adsorption onto the GAC, and the removal of substances that are effectively removed by PACAS (benzotriazole and the sum of 4- and 5-methyl-1H-benzotriazole) is higher than with old GAC, where mainly biological degradation takes place.
- Aurea (BO_3) was compared with the ozonation reference at an efficiency of 80-85% for 7/11 indicator substances over the entire WWTP. This showed that:
  - For 7/11 substances, BODAC (BACF only) removes the same set of substances as ozonation, and for 4 additional substances, it achieves a very low (<30%) or negative efficiency. For BODAC/BACF, the removal mechanism is bioregeneration: adsorption and biological degradation.
  - By adding ozonation in the Aurea (BO_3) technology, advanced removal of more substances is achieved, and the overall removal is higher than with BACF alone.
  - Ozonation alone removes more substances and demonstrates higher efficiencies than Aurea (BO_3), thus covering a broader removal palette than Aurea (BO_3). For 9 of the 11 substances, Aurea (BO_3) achieves efficiencies similar to the ozonation reference. Exceptions to this are benzotriazole and the sum of 4- and 5-methyl-1H-benzotriazole, for which Aurea (BO_3) has a lower efficiency than ozonation.

In summary, whether a combination of technologies achieves removal of a broader palette[2] of substances depends on which removal mechanisms are combined and whether these mechanisms are complementary in terms of the removal of individual indicator substances. It can be concluded that combining adsorption and oxidation technologies leads to a higher removal efficiency (>70% and >80%) of several of the Dutch indicator substances, and therefore removal of a broader palette. When biological conversion in BACF is combined with ozonation (Aurea (BO_3)), greater removal of more substances is achieved than with BACF alone. However, the ozonation reference alone removes more substances more efficiently than the combination of biological degradation and activated carbon. This combination of technologies therefore does not achieve a broader removal palette.

2 The term 'broader' is explained in appendix 6. It means that a higher removal rate is achieved for more than the required minimum of 7 of the 11 the indicator substances.

THE EU DIRECTIVE

For each of the technologies and reference cases, overall removal efficiencies were estimated based on the indicator substances proposed in the revised EU Directive as well as the distribution of these substances over the two categories defined in the Directive (see Table 4.1 and Table 2.2). It should be noted that in doing so, annual averages were used, as applied in the IPMV, rather than the minimum per-sample removal efficiency required under the EU Directive.

The assumed activated sludge removal efficiency for the standard WWTP can be taken as 40% for the proposed EU indicator substances, like for the Dutch indicator substances (see Table 4.1). However, this is dependent on the extent to which the proposed EU indicator substances are actually present in wastewater. Several of the envisaged EU indicator substances, particularly, amisulpride, candesartan and clarithromycin, are not typically present at sufficient levels in influents and effluents of Dutch WWTPs (Mulder, 2021). This is also why these are not included as indicator substances in the Netherlands. The proposed EU indicator substance citalopram is sufficiently present, but was excluded as a Dutch indicator substance because of a potentially too high removal efficiency in the activated sludge (>50%) (Mulder, 2021). This does not mean, however, that amisulpride, candesartan and clarithromycin are entirely absent from Dutch WWTP influents and effluents. Whether they are present depends on the discharges into the sewer of the particular WWTP (Mulder, 2023).

The EU Directive states that if fewer than 6 substances can be measured at sufficiently high concentrations, the responsible authority may, if needed, designate other substances in order to calculate the minimum removal percentage. It is not yet known how this part of the revised EU Directive will be transposed into legislation in the Netherlands.

The variability in removal efficiency in activated sludge appears to be greater for the proposed EU indicator substances than for the Dutch indicator substances. This also implies a greater variation in total removal efficiencies of WWTPs (effluent relative to influent). The 'EU activated sludge removal efficiency' is dependent on what substances are present in the influent of the WWTP and can drop to 25% instead of 40% if not all EU indicator substances are measured (see Mulder, 2023). In Table 4.1, efficiencies for the reference technologies are presented based on indicator substances that are sufficiently present in Dutch influents and effluents. Citalopram is included, while amisulpride, candesartan and clarithromycin are not. Consequently, the annual removal efficiency of the EU substances in activated sludge has been estimated at 25-35%, with the lower limit of annual efficiency assumed to be somewhat lower (Mulder, 2023).

This means that the actual removal efficiency of the EU substances in the activated sludge process at a given WWTP strongly influences the overall removal efficiency of a micropollutant removal technology (influent—effluent). If this overall removal efficiency is too low, it may be necessary to adjust the design criteria presented in the factsheets in appendix 5 (e.g., by applying a higher dosage).

In addition to differences in the substances themselves, the currently known differences between the EU and IPMV methodologies are as follows:

- Under the revised EU Directive, the removal in every sample must be greater than 80%, with a limited number of exceptions (out of 24 samples per year, at least 21 must comply). The IPMV uses annual removal efficiency.
- The EU provisions assume that sampling takes place under DWF conditions. This is comparable to the methodology applied in the IPMV, where DWF is defined as the flow up to 1.2 x (average dry weather flow + standard deviation) or 1.3 x median daily flow (STOWA 2023-45), and which was then used in the IPMV to make a translation into the annual flow. The EU Directive provides no further definition of DWF.
- The EU Directive divides substances into two categories with a prescribed ratio. This means that the removal mechanism or the combination of removal mechanisms used by the applied technologies have an influence on the removal efficiency. If a technology can achieve a high efficiency removal for several substances in both categories, this will be more advantageous than highly efficient removal only in one category. This links back to the earlier discussion regarding the effect of combining technologies (see also appendix 6).

Table 4.1 presents removal efficiencies based on the proposed EU indicator substances and Dutch indicator substances for a standard 100,000 PE WWTP for the ozonation, PACAS and GAC reference technologies and the innovative technologies investigated during the IPMV. The information in the table is based on expert opinions and preliminary findings from pilot and activated sludge installations in the Netherlands. It should be regarded as a rough indication of the differences between the proposed EU substances and the Dutch indicator substances. The figures should certainly not be interpreted as absolute values.

Table 4.1 shows that for most technologies a removal efficiency of 75-80% can be expected on an annual basis.

4.1.2 CO_2 FOOTPRINT

REFERENCE TECHNOLOGIES

Table 4.2 presents the CO_2 footprint for the reference technologies for a standard 100,000 PE WWTP. With the additional technologies, the CO_2 footprint of the WWTP increases by 39%, 94% and 129% for, respectively, the ozonation, PACAS and GAC reference cases.

Of the three reference cases, the relative CO_2 footprint of ozonation is the lowest, at 109 g CO_2/m^3 treated and 77 g CO_2/m^3 WWTP influent. At the other end of the spectrum, GAC has the highest CO_2 footprint, at 361 g CO_2/m^3 treated and 253 g CO_2/m^3 WWTP influent.

The CO_2 footprint of ozonation is due mainly to the raw material (pure oxygen) and the energy required to generate O_3 from that oxygen and introduce it into the system. For PACAS, energy consumption is only marginally higher than for the WWTP as a whole and the CO_2 footprint is determined primarily by the production and use of the PAC, which is dosed at 20 mg/l. For GAC, fresh or regenerated GAC is needed every 4-6 months, which is the main reason why this technology has the highest CO_2 footprint among the three references. As with ozonation, energy consumption is higher for GAC than for PACAS, though in the case of GAC this is mainly due to the required pumping head. See Figure 4.1.

TABLE 4.2 **CO_2 FOOTPRINT FOR WWTP AS A WHOLE AND REFERENCE TECHNOLOGIES (100,000 PE)**

Parameter	Unit	WWTP	PACAS ref	Ozonation ref[1]	GAC ref
CO_2 footprint total	ton CO_2/year	1,504	2,912	2,091	3,440
Increase relative to WWTP	%		94%	39%	129%
Volume treated	m^3/year	0	7,665,000	5,365,500	5,365,500
WWTP influent	m^3/year	7,665,000	7,665,000	7,665,000	7,665,000
CO_2 footprint micropollutant removal	g CO_2/m^3 treated		184	109	361
CO_2 footprint micropollutant removal	g CO_2/m^3 WWTP influent		184	77	253

[1] The IPMV started in 2018 with a reference case of ozonation + sand filtration (SF). In the current evaluation, that reference has been updated to ozonation only. If the additional assumptions for CO_2 footprint are applied to sand filtration and the resulting footprint for sand filtration added to the current ozonation footprint, the total becomes 2,279 tons CO_2/year, corresponding to, respectively, 145 and 101 g CO_2 per m^3 treated and per m^3 WWTP influent.

RELATIVE CO_2 FOOTPRINT

The relative CO_2 footprint was calculated in relation to both the volume (m^3) treated using the technology and the total influent volume across the entire WWTP. The first value provides insight into the CO_2 footprint of the technology itself. In the second value, the bypass is also included, therefore giving a better picture of the CO_2 footprint for the WWTP as a whole. This allows better comparisons to be made for the WWTP as a whole in cases where the bypass flow varies.

Figure 4.1 presents these relative footprints for the references and the technologies being compared. SF + UV/H_2O_2 has been truncated in the table for the sake of readability. Its footprint of 717 g CO_2 per m^3 treated and 574 g CO_2 per m^3 WWTP influent is that high that differences between the other technologies would no longer be visible in the graph.

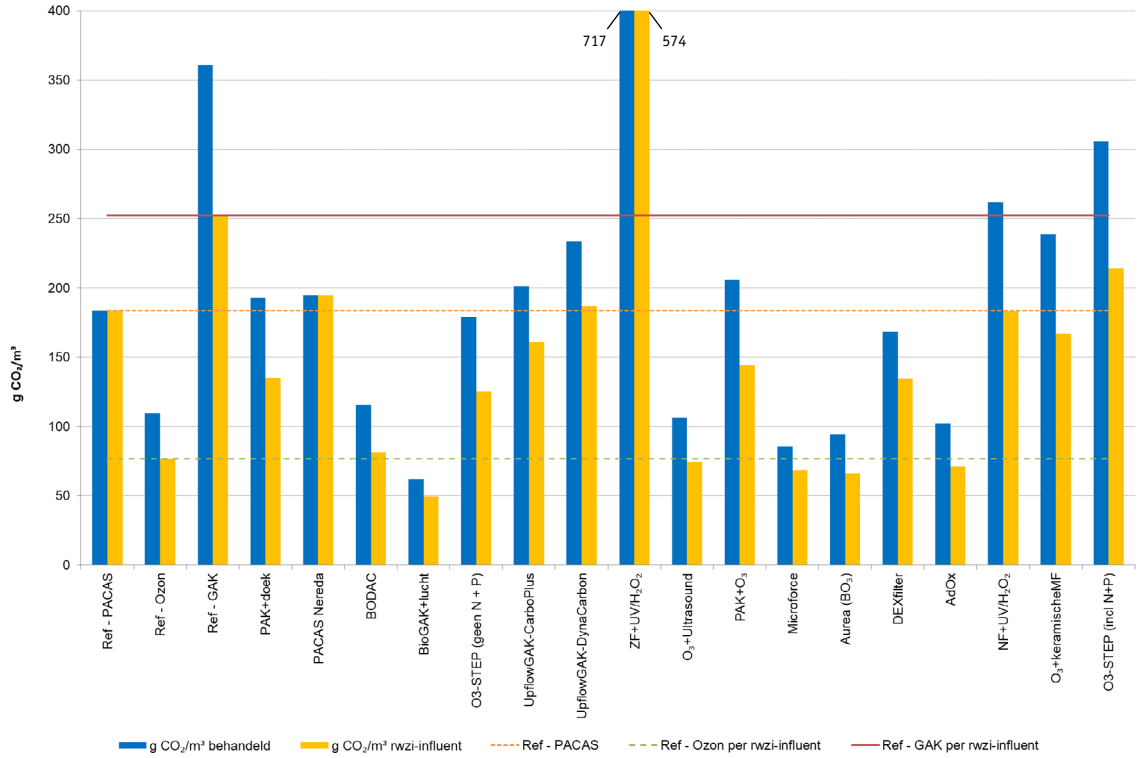
The figure, furthermore, shows that all of the other technologies have a smaller CO_2 footprint than the GAC reference (red line in graph). A few technologies, such as PACAS Nereda, upflow GAC-DynaCarbon and NF + UV/H_2O_2, have a similar or slightly higher CO_2 footprint compared to the PACAS reference (orange dashed line), but most of the technologies fall below this level. The most favourable CO_2 footprints are those for Bio-GAC + air, BODAC, O_3 + ultrasound, MicroForce, Aurea(BO_3) and AdOx. These are similar or lower than the most favourable reference, namely ozonation (green dashed line).

Among the technologies with the most favourable CO_2 footprint, additional pilot research is needed for O_3 + ultrasound and AdOx to enable more reliable assessments. In both these cases, the CO_2 footprint may turn out to be higher or lower than currently estimated.

To the right of the graph is the CO_2 footprint of O3-STEP including N and P removal. The difference compared to O3-STEP without N and P removal is the dosing of metal salts and methanol and a higher backwash water flow (10% instead of 1%). This increases the CO_2 footprint, though it remains below that of the GAC reference. With N and P removal, the O3-STEP technology can be utilised to achieve tighter effluent standards, such as those set by the Water Framework Directive.

If the other technologies included dosing for additional P and/or N removal, their CO_2 footprint would also be higher than shown in Figure 4.1.

FIGURE 4.1 **RELATIVE CO_2 FOOTPRINT OF TECHNOLOGIES FOR MICROPOLLUTANT REMOVAL*,****



* The CO_2 footprint of PAC + O_3 per m^3 treated is based on the 70% post-treatment annual flow.

** The CO_2 footprint of SF + UV/H_2O_2 is not presented in the graph and is 717 and 574 g CO_2, respectively, per m^3 treated and per m^3 WWTP influent.

TABLE 4.3 **RELATIVE CO_2 FOOTPRINT OF TECHNOLOGIES**

Relative CO_2 footprint	Technology
<85 g CO_2/m^3 WWTP influent	Ozonation reference
	BODAC
	Bio-GAC + air
	Aurea (BO_3)
	AdOx
	O_3 + ultrasound
	MicroForce
85-120 g CO_2/m^3 WWTP influent	-
120-160 g CO_2/m^3 WWTP influent	PAC + cloth filtration
	PAC + O_3
	O3-STEP (without N and P removal)
	DEX filter
160-200 g CO_2/m^3 WWTP influent	PACAS reference
	PACAS Nereda
	Upflow GAC
	NF + UV/H_2O_2
	O_3 + ceramic MF
>200 g CO_2/m^3 WWTP influent	GAC reference
	SF + UV/H_2O_2
	O3-STEP (with N and P removal)

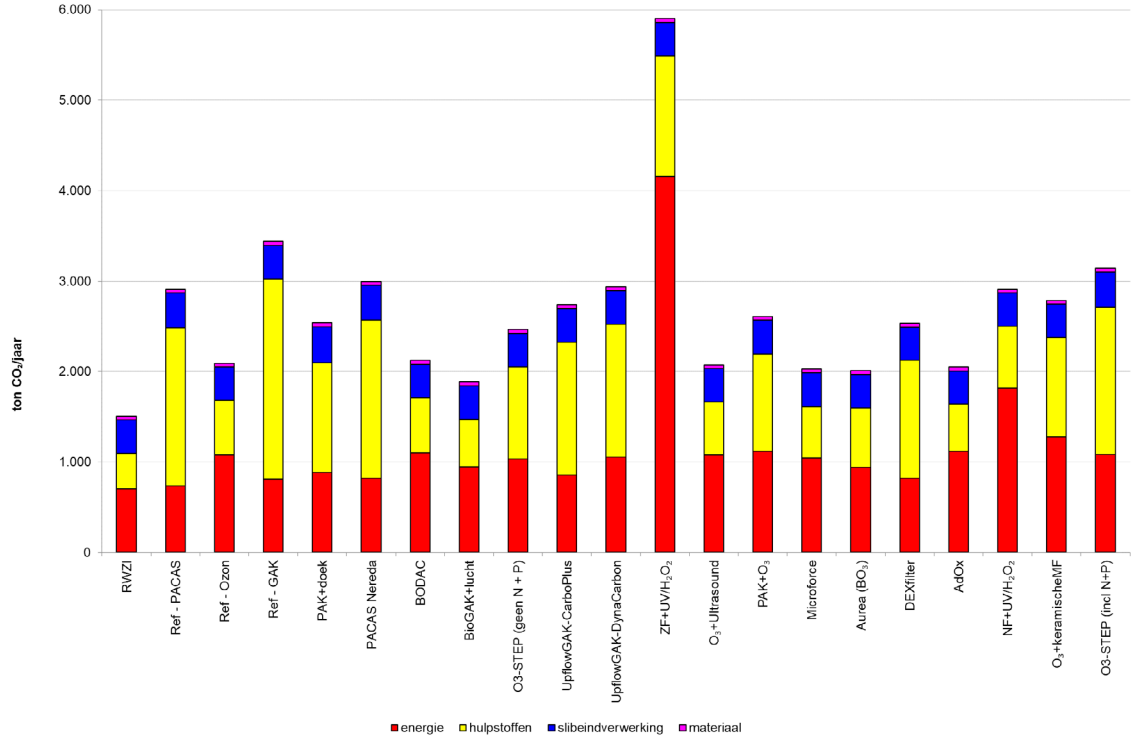
ABSOLUTE CO_2 FOOTPRINT AND BREAKDOWN OF THE FOOTPRINT

Figure 4.2 presents the CO_2 footprints of the different technologies for the standard 100,000 PE WWTP at 150 g COD, broken down into energy, process inputs/chemicals, final sludge processing and materials. The CO_2 footprints for final sludge processing and materials are very similar. The main differences are found in the CO_2 footprints for energy and for process inputs/chemicals. These can be important factors in the selection of a technology for a

particular location, for example, if there is congestion of the power grid or an objective to minimise the use of process additives.

Figures 4.3 through 4.6 provide a further breakdown of the CO_2 footprint of energy consumption and process inputs/chemicals for each technology concept.

FIGURE 4.2 **TOTAL CO_2 FOOTPRINT FOR THE ENTIRE WWTP, INCLUDING TECHNOLOGIES FOR MICROPOLLUTANT REMOVAL (STANDARD 100,000 PE WWTP AT 150 G COD)**

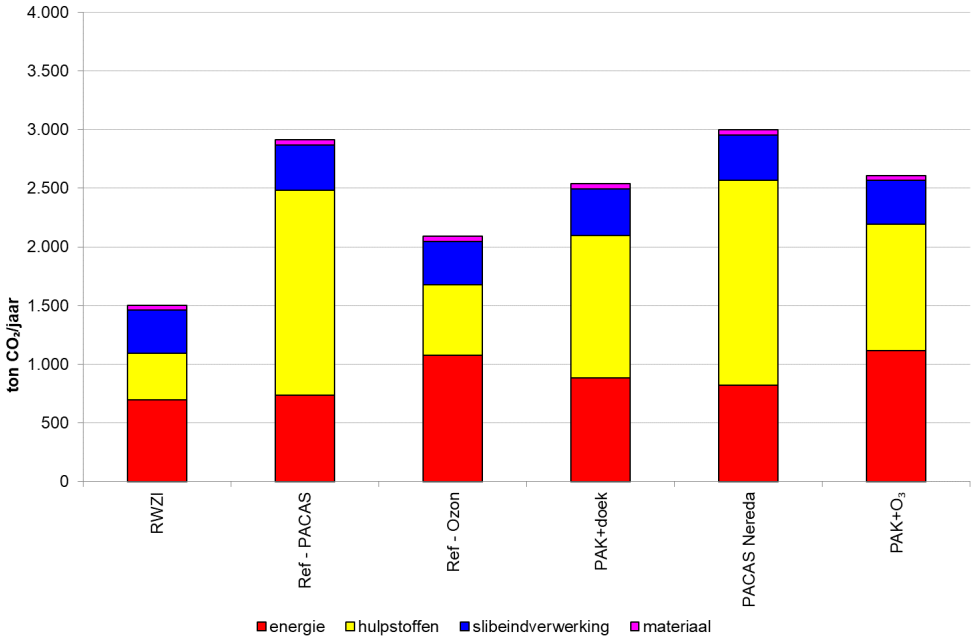


TECHNOLOGIES WITH PAC

Looking at the PAC adsorption technologies (see Figure 4.3), it can be seen that PACAS Nereda, which is a similar technology to the PACAS reference, has a slightly higher CO_2 footprint. This is caused by the higher energy consumption, as the PAC has to be dosed in a shorter period of time and pumped up to a greater height than in a conventional treatment installation. Nonetheless, the energy consumption estimated here seems somewhat on the high side. Additional operational experience is needed to establish what the real difference is with a conventional PACAS installation.

The combined technologies PAC + cloth filtration and PAC + O_3 both have a lower total CO_2 footprint than the PACAS reference case, and their CO_2 footprint is higher than for the ozonation reference. PAC + O_3 requires oxygen as a process input, but since the PAC dose (7.5 mg/l) is less than half that for PACAS, the overall contribution of process additives in both combined technologies is lower than in the PACAS reference. Similarly, the PAC dosage in PAC + cloth filtration, at 10 mg/l, is lower than that in PACAS. However, the combined technologies require additional electricity: for pumping the effluent, for filter operation (in PAC + cloth filtration) and for the ozonation component (in PAC + O_3).

FIGURE 4.3 **TOTAL CO_2 FOOTPRINT FOR THE ENTIRE WWTP, INCLUDING THE TECHNOLOGIES FOR MICROPOLLUTANT REMOVAL USING PAC (STANDARD 100,000 PE WWTP AT 150 G COD)**

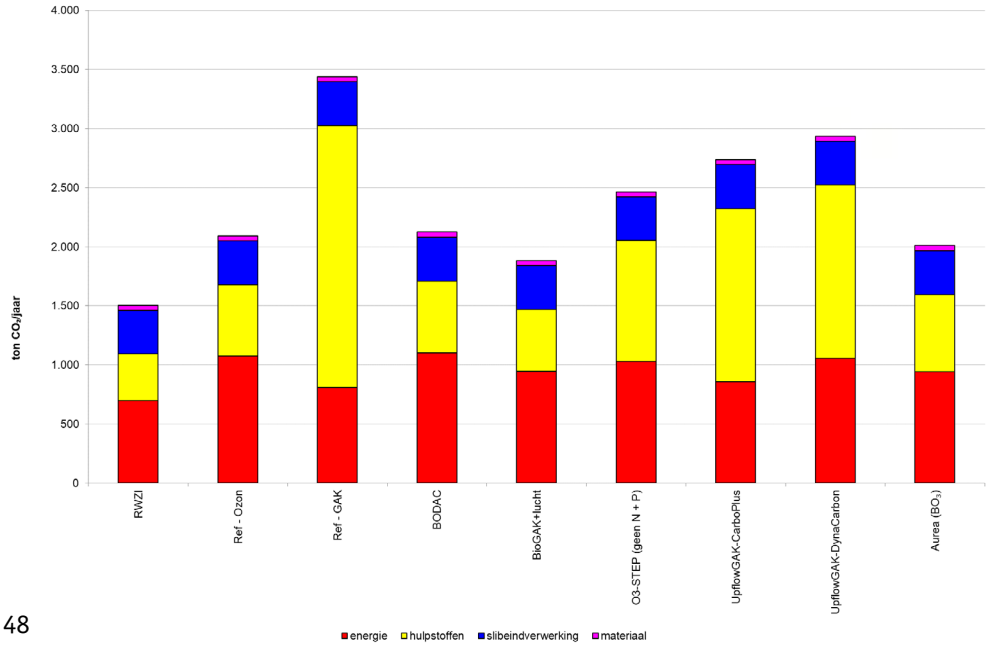


TECHNOLOGIES WITH GAC

Comparing the GAC adsorption technologies (Figure 4.4), the contribution of energy to the CO_2 footprint for CarboPlus and GAC is similar, whereas it is higher for all the other technologies. This is in part because of the additional pumping head or pressure requirements, as in BODAC, Bio-GAC + air and DynaCarbon, or due to the production and addition of ozone, as in O3-STEP, MicroForce and Aurea (BO_3).

All of the technologies have a longer GAC service life compared to the GAC reference, and the contact time (EBCT) is shorter. This reduces annual GAC consumption by more than 90% for the aerated GAC filters and by some 40-70% for the non-aerated GAC filters. See also the specific design assumptions for the GAC technologies in section 3.4.3.

FIGURE 4.4 **TOTAL CO_2 FOOTPRINT FOR THE ENTIRE WWTP, INCLUDING TECHNOLOGIES FOR MICROPOLLUTANT REMOVAL USING GAC (STANDARD 100,000 PE WWTP AT 150 G COD)**

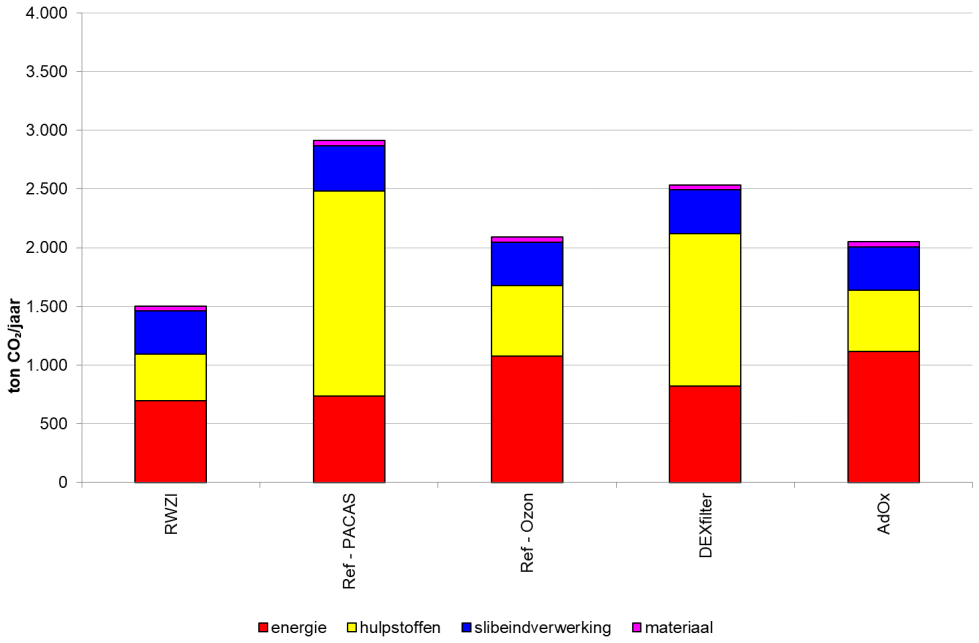


OTHER ADSORPTION TECHNOLOGIES

For the technologies that use other adsorption materials (Figure 4.5), the CO_2 footprint of DEXSORB (DEX filter) and zeolite (AdOx) was calculated. DEXSORB results in a one-third lower footprint for process inputs/chemicals compared to PACAS, while zeolite results in a reduction of nearly 95%. DEXSORB is commercially available, whereas the granular zeolite used for AdOx was specially developed for the IPMV pilot. However, because DEXSORB regeneration is done off-site, its CO_2 footprint is included under process inputs/chemicals. By contrast, regeneration of AdOx is carried out at the WWTP using ozone, meaning its regeneration is reflected mainly in energy consumption.

For both technologies, additional pilot research is needed to determine the CO_2 footprint with more certainty, as it could turn out to be either more or less favourable (see chapter 5).

FIGURE 4.5 TOTAL CO_2 FOOTPRINT FOR THE ENTIRE WWTP, INCLUDING MICROPOLLUTANT REMOVAL USING OTHER ADSORPTION TECHNOLOGIES (STANDARD 100,000 PE WWTP AT 150 G COD)

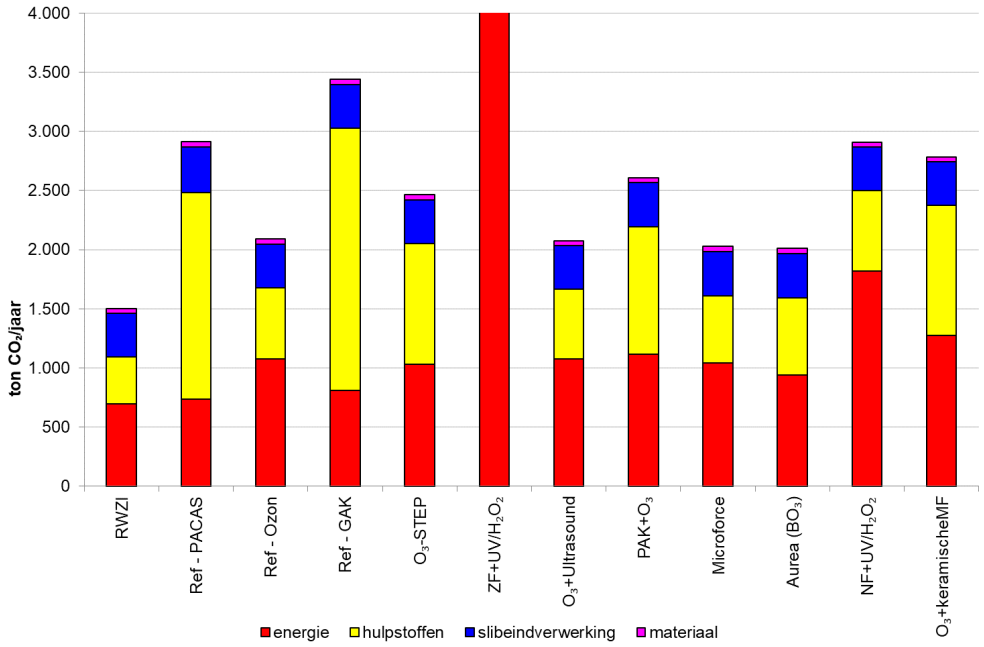


OXIDATIVE TECHNOLOGIES

Figure 4.6 presents the breakdown of the CO_2 footprint for the oxidative technologies. It is notable that despite similar or lower specific ozone use (see Table 3.8), the contribution of process inputs/chemicals is lower only for MicroForce and O_3 + ultrasound. The other technologies are combined systems that require activated carbon or other additives. For them, the lower energy consumption associated with the reduced specific ozone dosage is offset by the energy consumption of the other technology in the combination. Energy consumption is generally comparable to ozonation, mainly because a minimum pumping head of 8 m was assumed across all technologies.

The exception, as also previously indicated, is SF + UV/H_2O_2, for which energy consumption is much higher. Energy consumption for NF + UV/H_2O_2 is also greater, by about 40%, while the energy demand for O_3 + ceramic MF is slightly more than 30% higher than the ozonation reference. Nonetheless, both NF + UV/H_2O_2 and O_3 + ceramic MF produce a higher quality effluent, see discussion in section 4.2.4, 4.2.6 and 4.2.7.

FIGURE 4.6 **TOTAL CO_2 FOOTPRINT FOR THE ENTIRE WWTP, INCLUDING TECHNOLOGIES FOR MICROPOLLUTANT REMOVAL USING OXIDATIVE TECHNIQUES (AND FILTRATION) (STANDARD 100,000 PE WWTP AT 150 G COD)***

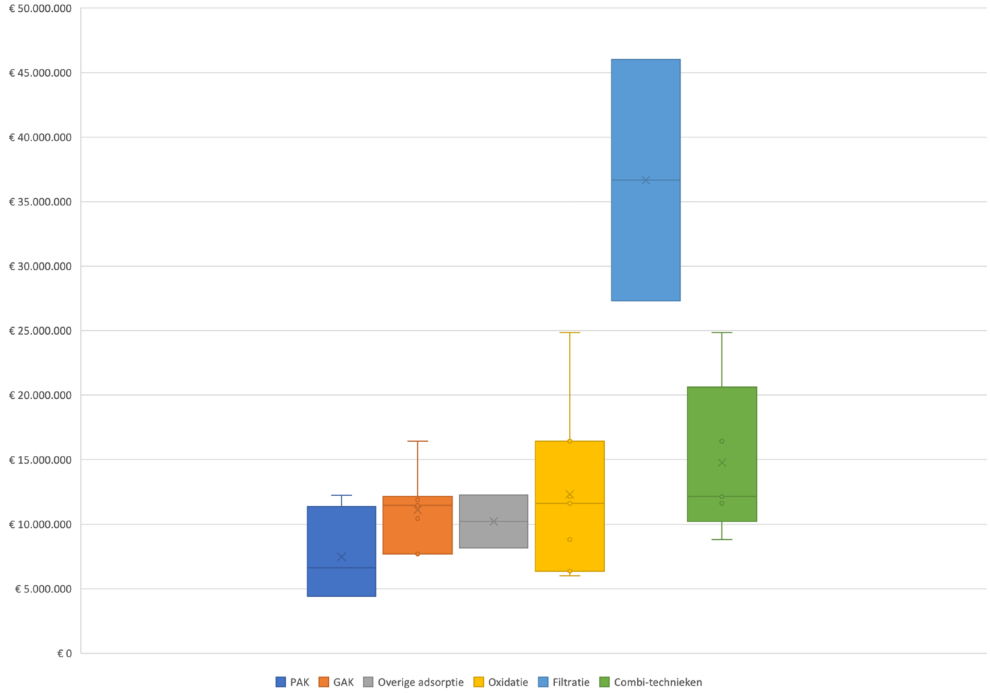


* For the sake of readability, CO_2 values for SF + UV/H_2O_2 are not shown in full in the figure. CO_2 values for energy, process inputs/ chemicals, final sludge processing and materials amount to 4,157, 1,330, 369 and 44 tons CO_2/year, respectively.

4.1.3 COSTS

The foundation costs estimated with the 2018 reference values, as reported in the pilot studies (see appendix 1), were adjusted for inflation by applying a factor of 1.38 to yield up-to-date foundation cost indications for the current evaluation (2024). In addition, some costs were adjusted to reflect a removal efficiency of 80% instead of 70%. To assess whether these updated indicative costs provide a realistic picture of the actual capital expenditures faced by water authorities, the costs of real projects in the Netherlands were requested. The updated (2024) costs of the reference cases are presented in Table 3.2. Significant cost differences were found between the pilot studies for a 100,000 PE WWTP and more recently implemented projects, particularly for PACAS technologies. Foundation costs were found to vary widely depending on the method of procurement. Therefore, a correction for this was incorporated into the foundation cost estimates for all PACAS technologies.

FIGURE 4.7 **FOUNDATION COSTS PER TECHNOLOGY TYPE (INCL. VAT) FOR 100,000 PE WWTP***



* combination techniques are PAK+O_3, O_3-STEP, Aurea (BO_3), Microforce and ZF+UV/H_2O_2

Figure 4.7 provides an overview of the foundation costs associated with all the considered technologies. The technologies are grouped into categories, as set out in Table 3.3. The filtration technologies are not included here in the oxidation category, but shown only under filtration. As costs are dependent on many factors the figures provided here should be read not as absolute values but as indicative amounts for comparison. For the same reason, costs are expressed as ranges.

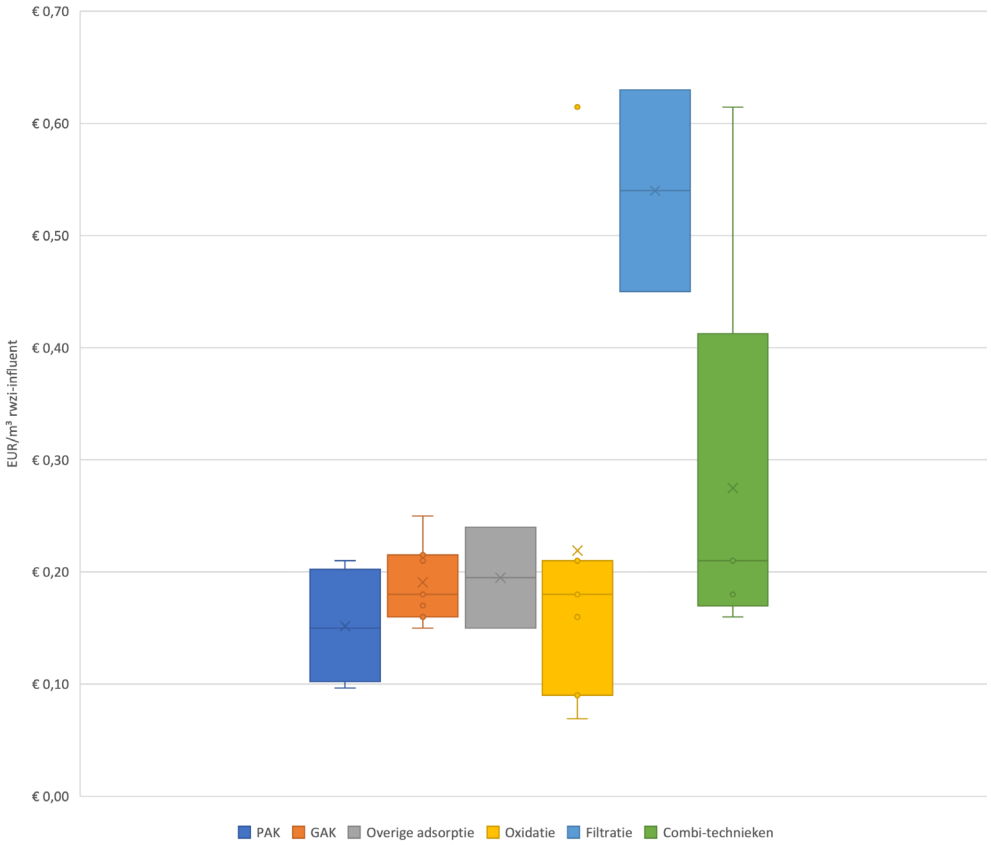
The results show significantly higher foundation costs for filtration technologies. In this regard, it is worth noting that these are not usually applied specifically for the removal of micropollutants, and they do have other advantages (see section 3.6). For ozonation combined with ceramic microfiltration, the updated foundation cost estimate came out too high, as recent reference projects indicate lower real foundation costs. However, due to the short project timeline, that information could no longer be included in the current report. Follow-up research is recommended to update the foundation costs for ozonation combined with ceramic microfiltration based on more recently completed projects.

For PAC technologies, the range lies between €4 and €12 million, with the PACAS reference at the lower end. For GAC technologies, the range is between €7.5 and €12 million. The GAC reference has foundation costs of some €10 million. The oxidation category contains a wide variety of technologies. Foundation costs for the ozonation reference are approximately €6 million, which is at the lower end of the range. Combined technologies are significantly more expensive, up to some €16 million, with UV + H_2O_2 being an outlier to approximately € 25 million.

The annual costs (capital and operating expenditure) were, wherever possible, linked to consumables, such as electricity and process inputs/chemicals, as reported in the factsheets in appendix 5. Where specific consumption data were not available, the corresponding operating costs from the pilot studies were used, adjusted to the 2024 cost benchmarks.

Based on these data, costs were calculated per m^3 of effluent treated and per m^3 over the entire WWTP. As noted earlier, costs depend on many factors, such as project delivery approach, the cost estimation method and the procurement strategy. It is therefore not meaningful to directly compare the costs of the different technologies per cubic meter. There are strong similarities within the technology categories. The ranges presented here should be interpreted as orders of magnitudes for the different technology types.

FIGURE 4.8 **ANNUAL COSTS €/M³ WWTP INFLUENT (INCL. VAT, 2024 PRICE LEVEL) FOR 100,000 PE WWTP***



* combination techniques are PAK+O_3, O_3-STEP, Aurea (BO_3), Microforce and ZF+UV/H_2O_2

The technologies are again divided into the same categories as in Figure 4.7. It is notable that the costs of PAC, GAC, and other adsorption and oxidation technologies are relatively low, at less than €0.25 per m^3 WWTP influent. For the DEX filter specifically, the updated cost of the adsorption material (cyclodextrins) may be overestimated in this evaluation. It is recommended that future research update the costs of cyclodextrins based on the current bulk price. PAC and oxidation technologies have the lowest costs, with these categories including the reference technologies. The oxidation category contains a variety of different technologies, and this is reflected in the wide variation with regard to costs. The majority, however, are of an order of magnitude similar to PAC and GAC. Filtration technologies are considerably more expensive (ranging from €0.45 to more than €0.60 per m^3). The combination technologies (also included under the other categories) are generally at the higher end of the cost ranges for the various categories. The large spread in the figure (green bar) is mainly due to the higher costs of technologies combined with filtration (SF + UV/H_2O_2), since most of the combined technologies are around €0.20 per m^3.

Annual costs can be broken down into capital and operational expenditure. Figure 4.9 shows a percentage distribution of capital and operating costs per technology, thus providing insight into each technology's cost structure. Operating costs can be further broken down into energy, process additives/chemicals and other. This also reveals which technologies are particularly sensitive to, for example, large changes in prices of process additives or shifts in prices or availability of energy/electricity (Figure 4.9).

FIGURE 4.9 **ANNUAL COSTS SPLIT INTO CAPITAL AND OPERATIONAL EXPENDITURE. NOTE: THE BREAKDOWN IS EXPRESSED AS A PERCENTAGE PER TECHNOLOGY AND IS NOT INDICATIVE OF ABSOLUTE COSTS.**

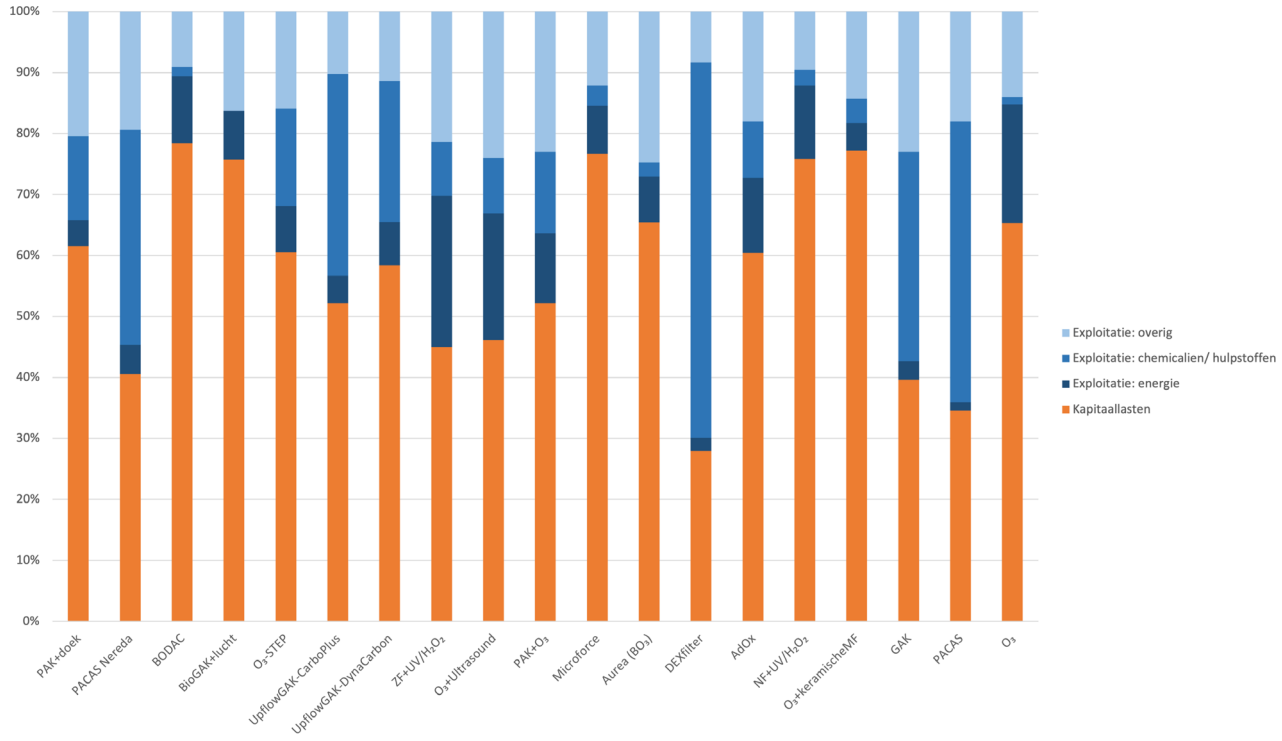
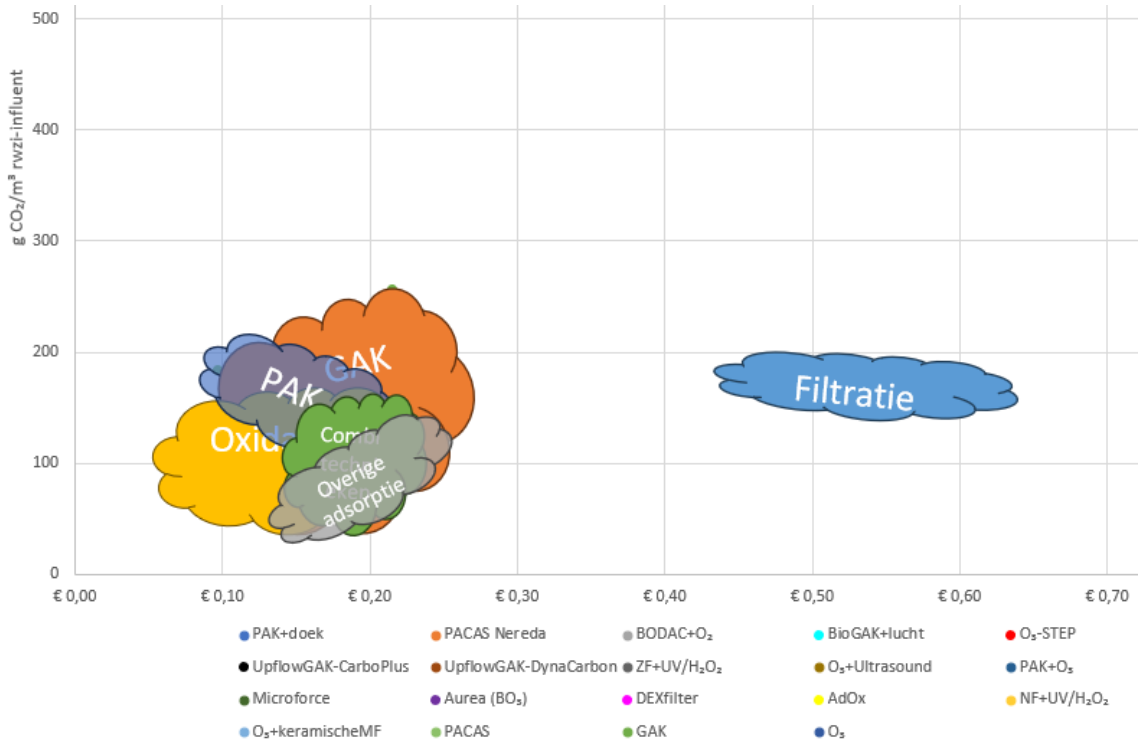


Figure 4.10 plots the CO_2 footprint against technology costs per m^3 WWTP influent. One data point falls outside the chart: SF + H_2O_2/UV. This is due to the much higher CO_2 footprint for this technology, at 574 g CO_2/m^3 WWTP influent, compared to the other technologies. GAC, PAC, oxidation and other adsorption technologies all cluster closely together, with the greatest variation found among the GAC technologies. Though filtration technologies are much more expensive, their CO_2 footprint is in the same order of magnitude as the other technologies. It should be noted that the clusters for filtration technologies and other adsorption technologies could still shift, as these technologies currently have a lower TRL.

FIGURE 4.10 RELATIONSHIP OF CO_2 FOOTPRINT AND COSTS PER M^3 WWTP INFLUENT



4.1.4 SENSITIVITY ANALYSIS

Based on the experiences gained in recent years with the removal of micropollutants from wastewater in the Netherlands, three important sensitivities with regard to costs can be identified. These were investigated in this sensitivity analysis as follows:

- The price of activated carbon
- The electricity price
- The variation in foundation costs (+/-30%)

Regarding the CO_2 footprint, the main differences found related to energy and process additives. For these components, the CO_2 reference values are based on fossil sources. Yet, many water authorities purchase 'green' electricity or electricity from more sustainable sources than fossil fuels. The IPMV also tested more sustainable powdered carbons. Thus, technology CO_2 footprints were recalculated for two cases:

- Use of 'green' (renewable) electricity generated in the Netherlands
- More sustainable PAC

See Table 2.3 for the CO_2 reference values applied.

In addition, for this evaluation all of the post-treatment technologies were recalculated using a pumping head of 8 m. For comparability, the service life of the GAC in BODAC, Bio-GAC + air and Aurea (BO_3) was extended to 15 years, though currently only BODAC has been in operation for this length of time (almost 15 years). This affects both costs and CO_2 footprint.

PRICE OF ACTIVATED CARBON

During the past 5 years, the price of activated carbon rose sharply and eventually decreased again somewhat. For example, the price of a suitable PAC was approx. €4 per kg in 2023, though it later dropped to €2.75 per kg. Table 4.4 presents the costs as estimated in 2018, and

the updated costs for 2024. Since the IPMV began in 2018, the costs for GAC and PAC have risen by 13% to 80%. In this regard, the moment of procurement is determinative, because that is when the price is fixed for a particular period. The table presents sensitivity estimates for different types of activated carbon.

TABLE 4.4 REFERENCE PRICE FOR ACTIVATED CARBON (INCL. VAT)

Parameter	Unit	IPMV 2018	Update 2024	Increase 2024 relative to 2018	Sensitivity relative to 2024
Powdered activated carbon	per kg	€ 2.00	€ 2.75	38%	+50%
Granular activated carbon	per m^3	€ 1,200	€ 1,350 [1]	13%	+25%
Reactivated granular activated carbon	per m^3	€ 500	€ 900	80%	+50%

[1] €3,000 per ton and 450 kg/m^3.

Because of the sharp cost increases in recent years and the importance of the timing of procurement, this sensitivity analysis examined the effect of possible increases in the price of activated carbon on the annual costs of the different technologies per m^3 influent for the entire (100,000 PE) WWTP (Table 4.5). All PAC and GAC technologies are affected: the PACAS reference, PAC + cloth filtration, PACAS Nereda, PAC + O_3, the GAC reference, O3-STEP, UpflowGAC-CarboPlus, UpflowGAC-DynaCarbon, BODAC, Bio-GAC + air and Aurea (BO_3). In absolute terms, the cost increase has the greatest effect on the GAC reference technology and the smallest effect on BODAC, Bio-GAC + air and Aurea. Expressed as a percentage of annual costs, the effect is also greatest on the GAC reference technology, as well as the PACAS reference. Furthermore, the cost increase has a relatively large influence on PACAS Nereda and UpflowGAC-CarboPlus. This is due to the relatively high activated carbon consumption of these technologies.

TABLE 4.5 SENSITIVITY ANALYSIS OF INCREASED ACTIVATED CARBON COST (+50% PAC, +25% GAC, +50% REACTIVATED GAC) ON TOTAL ANNUAL COSTS

Technologies	Cost increase (€/m^3 WWTP influent)	Increase in total annual costs
PACAS reference	€ 0.02	23%
PAC + cloth filtration	€ 0.01	5%
PACAS Nereda	€ 0.02	18%
PAC + O_3	€ 0.01	5%
GAC reference	€ 0.05	23%
O3-STEP (without N and P removal)	€ 0.01	5%
UpflowGAC - CarboPlus	€ 0.02	13%
UpflowGAC - DynaCarbon	€ 0.02	9%
BODAC	€ 0.001	1%
Bio-GAC + air	€ 0.002	1%
Aurea (BO_3)	€ 0.002	1%

ELECTRICITY PRICE

The price of electricity has fluctuated significantly over the past 5 years. Since the IPMV began in 2018, the electricity price has risen by about 100% on average (Table 4.6). However, the moment of procurement is decisive here as well, as the price is fixed for a certain period at that time. This sensitivity analysis therefore looks at the effect of a 50% increase or decrease in electricity price relative to 2024.

TABLE 4.6 **APPLIED ELECTRICITY PRICE (INCL. VAT)**

Parameter	Unit	IPMV 2018	Update 2024	Increase 2024 relative to 2018
Electricity	per kWh	€ 0.10	€ 0.20	100%

All the technologies considered use electricity to a greater or lesser extent. This sensitivity analysis thus pertains to all the technologies. The largest effect is seen in the technologies that consume the most electricity, both in absolute terms (in total euros) and in relative terms (in relation to the total cost of the technology). These are SF + UV/H_2O_2, O_3 + ultrasound and the O_3 reference.

TABLE 4.7 **SENSITIVITY ANALYSIS OF ELECTRICITY PRICE EFFECT (+/- 50%) ON TOTAL ANNUAL COSTS**

Technologies	Cost increase (€/m^3 WWTP influent)	Increase in total annual costs
PAC + cloth filtration	+/- € 0.00....	+/- 2%
PACAS Nereda	+/- € 0.00...	+/- 2%
BODAC + O_2	+/- € 0.01	+/- 6%
Bio-GAC + air	+/- € 0.01	+/- 4%
O3-STEP (without N and P removal)	+/- € 0.01	+/- 4%
UpflowGAC - CarboPlus	+/- € 0.00	+/- 2%
UpflowGAC - DynaCarbon	+/- € 0.01	+/- 4%
SF + UV/H_2O_2	+/- € 0.08	+/- 12%
O_3 + ultrasound	+/- € 0.01	+/- 10%
PAC + O_3	+/- € 0.01	+/- 6%
MicroForce	+/- € 0.01	+/- 4%
Aurea (BO_3)	+/- € 0.01	+/- 4%
DEX filter	+/- € 0.00	+/- 1%
AdOx	+/- € 0.01	+/- 6%
NF + UV/H_2O_2	+/- € 0.03	+/- 6%
O_3 + ceramic MF	+/- € 0.01	+/- 2%
GAC reference	+/- € 0.00	+/- 2%
PACAS reference	+/- € 0.00	+/- 1%
O_3 reference	+/- € 0.01	+/- 10%

FOUNDATION COSTS COSTS

The method of procurement can have a major impact on final foundation costs. When new technologies are being applied, an approach with a joint client-contractor team (see paragraph 2.7) is preferred; but proven technologies projects may be tendered on a (partly) turn-key basis. Regardless of the procurement form, there is always considerable uncertainty surrounding the foundation costs of technologies for micropollutant removal. Prices may vary widely depending on particular features of a WWTP, a water authority's priorities and requirements, and current market conditions. For this reason, a sensitivity analysis was carried out on the effect of 30% lower and 30% higher foundation costs. The ±30% was chosen indicatively to gain insight into the effect of fluctuations in foundation costs

As shown in Figure 4.9, foundation costs account for a much larger share of the total annual costs in some technologies than in others. For example, foundation costs (as annual capital expenditures) weigh relatively heavily in BODAC, Bio-GAC + air, MicroForce, NF + UV/H_2O_2 and O_3 + ceramic MF. In contrast, for DEX filter, the PACAS reference and PACAS Nereda, capital expenditures are relatively low compared to total annual costs. For these, the impact of foundation costs is more limited. That effect can be seen in Table 4.8.

TABLE 4.8 **SENSITIVITY ANALYSIS OF EFFECT OF A ±30% CHANGE IN FOUNDATION COSTS ON ANNUAL COSTS**

Technologies	Cost increase/decrease (€/m³ WWTP influent)	Increase/decrease in total annual costs
PAC + cloth filtration	+/- € 0.04	+/- 18%
PACAS Nereda	+/- € 0.02	+/- 12%
BODAC + O_2	+/- € 0.04	+/- 24%
Bio-GAC + air	+/- € 0.03	+/- 23%
O3-STEP (without N and P removal)	+/- € 0.04	+/- 18%
UpflowGAC-CarboPlus	+/- € 0.03	+/- 16%
UpflowGAC-DynaCarbon	+/- € 0.04	+/- 18%
SF + UV/H_2O_2	+/- € 0.08	+/- 13%
O_3 + ultrasound	+/- € 0.01	+/- 14%
PAC + O_3	+/- € 0.03	+/- 16%
MicroForce	+/- € 0.05	+/- 23%
Aurea (BO_3)	+/- € 0.03	+/- 21%
DEX filter	+/- € 0.02	+/- 8%
AdOx	+/- € 0.03	+/- 22%
NF + UV/H_2O_2	+/- € 0.10	+/- 23%
O_3 + ceramic MF	+/- € 0.14	+/- 23%
GAC reference	+/- € 0.04	+/- 19%
PACAS reference	+/- € 0.01	+/- 10%
O_3 reference	+/- € 0.01	+/- 15%

'GREEN' (RENEWABLE) ELECTRICITY

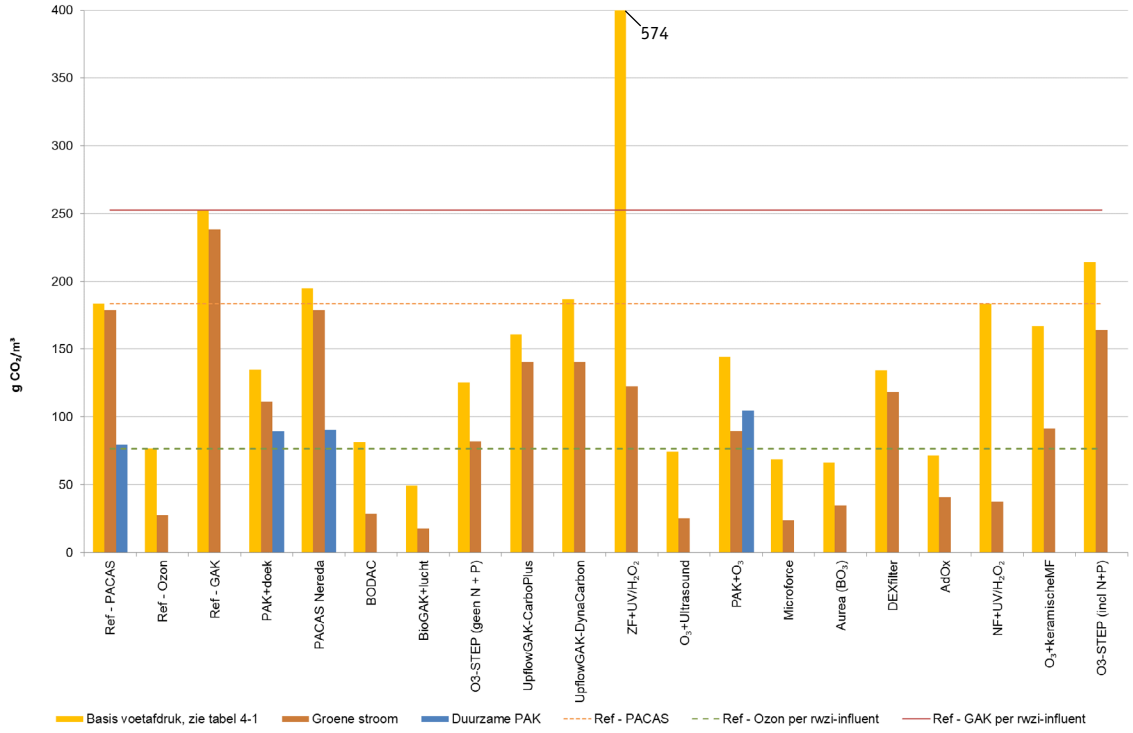
The CO_2 footprint reference value for Dutch 'green' electricity is 0 kg CO_2/kWh, compared to 0.536 kg CO_2/kWh for 'grey' (non-renewable) electricity (see Table 2.3). Figure 4.11 shows the change in the CO_2 footprint of the technologies when adjusting only the CO_2 reference value from 0.536 kg CO_2/kWh to 0 kg CO_2/kWh. Table 4.9 divides the technologies into lower and higher CO_2 footprint categories.

The results show that this change has the greatest effect on the technologies for which the CO_2 footprint is determined primarily by electricity consumption. The footprint of SF + UV/H_2O_2 and NF + UV/H_2O_2 decreases by 80%, making the footprint of NF + UV/H_2O_2 similar to that of the technologies that already had a low CO_2 footprint (see Table 4.9).

The CO_2 footprint of the ozonation reference, BODAC, Bio-GAC + air, O_3 + ultrasound and MicroForce drops by 65% with the use of 'green' electricity, mainly because of the electricity demanded for pumping and ozonation. The footprint of O3-STEP with N and P removal was already lower than that of the GAC reference, and with green electricity it drops below the CO_2 footprint of the two PACAS technologies.

The effect of procurement of green electricity is smallest for the PACAS technologies (reference -3%, Nereda -6%).

FIGURE 4.11 SENSITIVITY OF 'GREEN' ELECTRICITY AND MORE SUSTAINABLE PAC ON CO_2 FOOTPRINT*



* The yellow bars (baseline footprint) are the same as the yellow bars in Figure 4.1 and represent the situation with 'grey' (non-renewable) electricity and fossil-derived PAC.

TABLE 4.9 RELATIVE CO_2 FOOTPRINT AND SENSITIVITY OF 'GREEN' ELECTRICITY AND MORE SUSTAINABLE PAC

Relative CO_2 footprint	Baseline CO_2 footprint (see section 2.6)	'Green' electricity	Sustainable PAC
<50 g CO_2/m^3 WWTP influent		Ozonation reference BODAC Bio-GAC + air O3 + ultrasound MicroForce Aurea (BO_3) AdOx NF + UV/H_2O_2	
<85 g CO_2/m^3 WWTP influent	Ozonation reference BODAC Bio-GAC + air Aurea (BO_3) AdOx O_3 + ultrasound MicroForce	O3-STEP (without N and P removal)	PACAS reference Ozonation reference BODAC Bio-GAC + air Aurea (BO_3) AdOx O_3 + ultrasound MicroForce
85-120 g CO_2/m^3 WWTP influent		PAC + cloth filtration PAC+O_3 DEX filter O_3 + ceramic MF	PAC + cloth filtration PACAS Nereda PAC + O_3
120-160 g CO_2/m^3 WWTP influent	PAC + cloth filtration PAC+O_3 O3-STEP (without N and P removal) DEX filter	PACAS Nereda Upflow GAC SF + UV/H_2O_2	O3-STEP (without N and P removal) DEX filter

Relative CO_2 footprint	Baseline CO_2 footprint (see section 2.6)	'Green' electricity	Sustainable PAC
160-200 g CO_2/m^3 WWTP influent	PACAS reference PACAS Nereda Upflow GAC NF + UV/H_2O_2 O_3 + ceramic MF	PACAS reference O3-STEP (with N and P removal)	PACAS reference Upflow GAC NF + UV/H_2O_2 O_3 + ceramic MF
>200 g CO_2/m^3 WWTP influent	GAC reference SF + UV/H_2O_2 O3-STEP (with N and P removal)	GAC reference	GAC reference SF + UV/H_2O_2 O3-STEP (with N and P removal)

MORE SUSTAINABLE PAC

The CO_2 reference value for more sustainable (bio-based) powdered activated carbon is, at 4.54 kg CO_2/kg, 41% of the 11.06 kg CO_2/kg for conventional PAC (see Table 2.3) (STOWA 2020-19 and STOWA 2021-24). Figure 4.11 presents the effect of the application of more sustainable activated carbon on the CO_2 footprint of the four PAC technologies. Table 4.9 provides the breakdown of the technologies into lower and higher CO_2 footprint groups.

In contrast to the sensitivity for 'green' electricity, the CO_2 footprint of the PACAS reference and PACAS Nereda drops by some 55%, bringing their levels close to those of the technologies with a low CO_2 footprint (Table 4.9). The CO_2 footprint of these technologies is highly sensitive to PAC origin, making the use of more sustainable carbons in these technologies particularly attractive from a sustainability perspective.

For the combined technologies PAC + cloth filtration and PAC + O_3, the CO_2 footprint decreases by 25-35%.

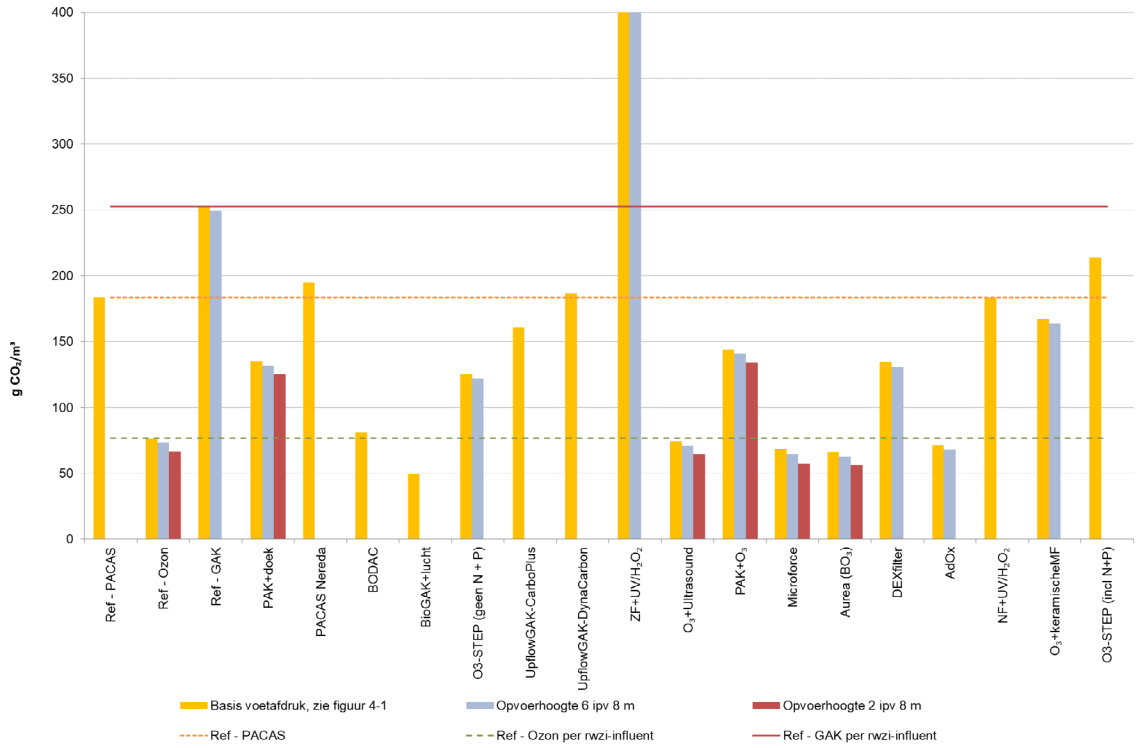
PUMPING HEAD 8 M VERSUS 2 M

In this evaluation, the pumping head for all downstream technologies was set at 8 m, unless a higher value is specified (BODAC, Bio-GAC + air, UpflowGAC). For the PACAS reference, PACAS Nereda and NF + UV/H_2O_2, no pumping head was included.

Some technologies are deliberately designed to operate with a low pumping head, and these are therefore slightly disadvantaged by this approach. In addition, factors such as the design of the ozonation system and site-specific characteristics may result in a lower pumping head.

This sensitivity analysis provides insight into the range between a very low pumping head of 2 m and the 8 m pumping head used in the calculations (Figure 4.12). It will not be possible to apply the same pumping head across all technologies; in this analysis the ozonation technologies were taken as the reference. For these and the other technologies, the CO_2 footprint was also calculated using a pumping head of 6 m.

FIGURE 4.12 **SENSITIVITY OF REDUCING THE PUMPING HEAD TO 6 M AND 2 M ON THE CO_2 FOOTPRINT***



* For SF + UV/H_2O_2, the footprint in the figure is capped for readability. The baseline footprint is 574 g CO_2/m^3 $_{WWTP\ influent}$, and at a pumping head of 6 m it is 570 g CO_2/m^3 $_{WWTP\ influent}$.

Lowering the pumping head from 8 to 2 m results in an approximately 15% lower CO_2 footprint for the ozonation reference, O_3 + ultrasound, MicroForce and Aurea (BO_3). For technologies with a higher 'baseline' footprint (PAC + cloth filtration and PAC + O_3), the reduction is 7%. Lowering the pumping head from 8 to 6 m reduces the CO_2 footprint of these technologies by 1-5%.

This also affects the annual costs of these technologies, though to a lesser degree, between 2% and 4% (Table 4.10).

TABLE 4.10 **SENSITIVITY ANALYSIS OF REDUCING THE PUMPING HEAD FROM 8 M TO 2 M ON ANNUAL COSTS**

Technologies	Reduction in total annual costs
PAC + cloth filtration	2%
O_3 + ultrasound	4%
PAC + O_3	2%
MicroForce	2%
Aurea (BO_3)	2%
O_3 reference	5%

GAC SERVICE LIFE

The Aurea (BO_3) pilot was carried out with saturated GAC that had been in use for 13 years at the ultrapure water plant (BODAC) in Emmen. The aerated continuous Bio-GAC pilot was carried out with fresh GAC and ran for about 1.5 years. Even though the Bio-GAC installation had only been in operation for 1.5 years, it is reasonable to assume a replacement interval of 15 years here as well since, like BODAC and Aurea (BO_3), it uses an aerated GAC filter. The current evaluation therefore assumed a service life of 15 years. For O3-STEP, the service life is

an important topic for further study. The effect of specific conditions in the filter on service life remains to be determined in real-world experience.

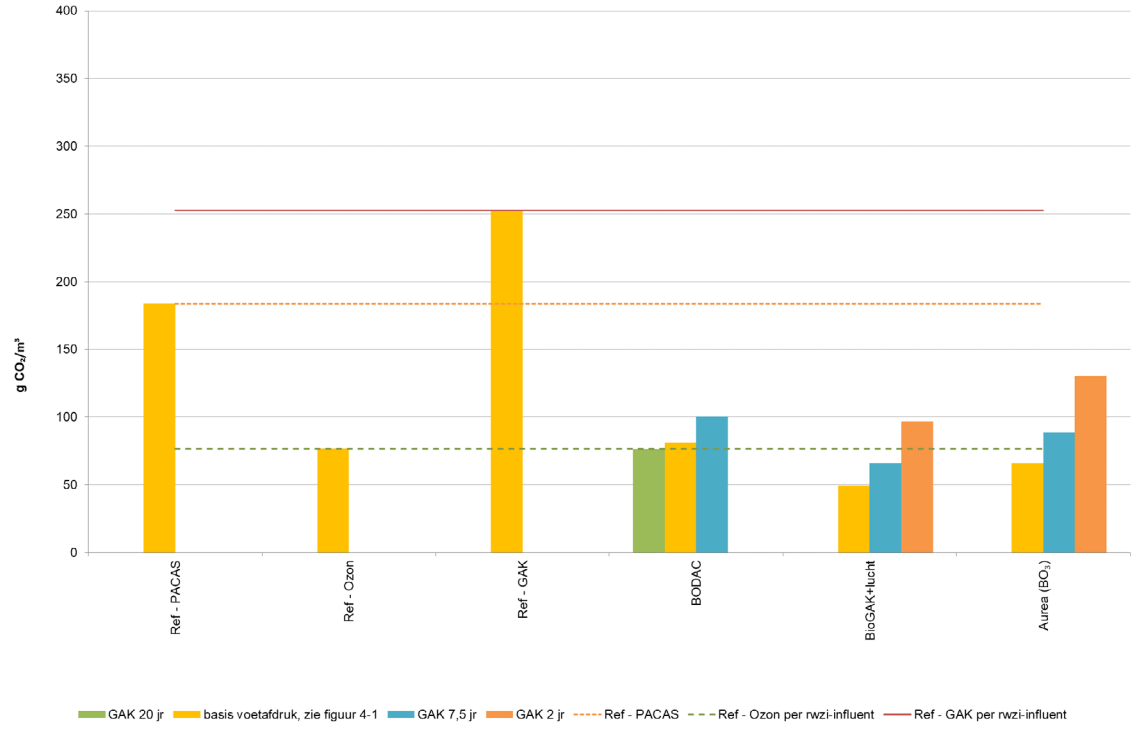
In the STOWA report on the pilot, a service life of 1.5 years was assumed for Bio-GAC + air. For a newly started BODAC and Aurea (BO_3), it is uncertain how these technologies will perform initially with fresh GAC and how long it will take before the filter reaches optimal biological performance. Given the presence of a pre-filter in BODAC, a longer service life can likely be assumed. Therefore, this sensitivity analysis employs a 2 and 7.5 year service life for Bio-GAC + air and Aurea (BO_3), using respectively, a combination of fresh and reactivated carbon and only fresh GAC. For BODAC, only the 7.5 year scenario with fresh GAC was calculated.

Figure 4.13 presents the results, in which the yellow bar indicates the baseline CO_2 footprint (from section 4.1.2) for a service life of 15 years. Increasing the service life in BODAC to 20 years reduces the CO_2 footprint by approximately 5%, while halving the service life (to 7.5 years) results in about a 25% higher CO_2 footprint. For Bio-GAC + air and Aurea (BO_3), halving the service life (from 15 to 7.5 years) increases the CO_2 footprint by about one-third, while a service life of 2 years roughly doubles the CO_2 footprint.

The CO_2 footprint of these technologies is thus very sensitive to the GAC service life, making this an important consideration when selecting a technology for a given WWTP. In this regard, building up practical experience remains an important objective, to gain greater certainty about the GAC service life.

For O3-STEP, a GAC service life of 2 years was assumed. Here, too, the service life could turn out to be shorter or longer than this baseline assumption. Considering the above, it can be assumed the CO_2 footprint of O3-STEP is also highly sensitive to the GAC service life.

FIGURE 4.13 **SENSITIVITY OF LONGER AND SHORTER GAC SERVICE LIFE ON THE CO_2 FOOTPRINT**



This also affects the costs of these technologies. If the service life proves to be shorter, and is closer to 2 years, costs increase by some 20% (Table 4.11).

TABLE 4.11 SENSITIVITY ANALYSIS OF LONGER AND SHORTER GAC SERVICE LIFE ON ANNUAL COSTS

Technologies	Service life	BODAC+O_2	Bio-GAC+air	Aurea (BO_3)
Percentage reduction in total annual costs	20 years	-1%		
Percentage increase in total annual costs	7.5 years	+3%	+3%	+4%
Percentage increase in total annual costs	2 years		+20%	+23%

4.2 QUALITATIVE PERFORMANCE OF TECHNOLOGIES

4.2.1 BIOASSAYS: ECOTOXICITY

The development of a methodology and measurements for assessing ecotoxicity has been a major added value of the IPMV pilot studies. Nonetheless, due to costs and time constraints, only a limited number of ecotoxicity measurements could be performed for each pilot study.

The reduction in ecotoxicity was assessed using bioassays, which indicated an average reduction of 50% or more over the total effluent of the WWTP for all of the technologies. For PACAS and GAC filters, the removal efficiency was around 50%, while for combined technologies, such as PAC + O_3, MicroForce and SF + UV/H_2O_2, reductions of 75% were achieved.

4.2.2 NUTRIENT REMOVAL CO-BENEFITS: AMMONIUM, NITRATE AND PHOSPHATE

Table 4.12 shows which technologies remove nutrients as well as micropollutants. A number of aspects merit noting:

- On carbon granules, bacteria can grow that can remove the adsorbed micropollutants (see section 3.4.1), bromate (see section 4.2.3) and nutrients (see below).
- Ammonium is (partly) nitrified in post-treatment aerated filter systems, such as BODAC, BioGAC + air, Aurea (BO_3) and MicroForce.
- O3-STEP can be implemented as a denitrifying and phosphorus-removing system by dosing methanol and metal salts. This option is not included in the costs and relative CO_2 footprint presented in Figure 4.1.
- Phosphate is automatically removed in PAC + cloth filtration systems, since coagulation with metal salts is required for PAC separation. If metal salts are already dosed in the water line for P removal, these can be reduced so that the net P removal remains unchanged. If dosing in the water line is not adjusted, the technology will provide additional P removal.
- Phosphate can additionally be removed in all post-treatment GAC filters. This is not currently accounted for in the presented CO_2 footprint and cost calculations.
- P bound to suspended solids is captured in all systems which remove suspended solids, such as GAC and filtration systems.

TABLE 4.12 CO-BENEFITS OF TECHNOLOGIES, CLASSIFIED BY REMOVAL MECHANISM FOR COMPARATIVE PURPOSES[1]

Removal mechanism and technology	Ammonium	Nitrate	Phosphate[2]	Remarks
Adsorption onto PAC				
PAC + cloth filtration	-	-	x (-)	() with $FeCl_3$ dosing
PACAS Nereda	-	-	-	
PAC + O_3	-	-	-	
Adsorption onto GAC				
O3-STEP (without N and P removal)	-	- (x[1])	- (x[1])	() with $FeCl_3$ and methanol dosing
Continuous upflow GAC	-	-	- (x[1])	() with $FeCl_3$ dosing
BODAC	x	-	- (x[1])	() with $FeCl_3$ dosing
Continuous Bio-GAC + air	x	-	- (x[1])	() with $FeCl_3$ dosing
Aurea (BO_3)	x	-	- (x[1])	() with $FeCl_3$ dosing
Adsorption onto other non-fossil materials				
DEX filter	- (x[1])	- (x[1])	- (x[1])	() Further research into the mechanism needed
AdOx	- (x[1])	-	-	() other zeolite composition[3]
Oxidative technologies and filtration technologies				
SF + UV/H_2O_2	-	- (x[1])	- (x[1])	() with $FeCl_3$ and methanol dosing on the sand filter
O_3 + ultrasound	-	-	-	
O3-STEP (without N and P removal)	-	- (x[1])	- (x[1])	() with $FeCl_3$ and methanol dosing
PAC + O_3	-	-	-	
MicroForce	x	-	-	
Aurea (BO_3)	x	-	- (x[1])	() with $FeCl_3$ dosing
NF and UV/H_2O_2	-	-	x	
O_3 + ceramic MF	-	-	-	

[1] X = removed in the technology, - = not removed in the technology, () = potentially removable (the 'remarks' column specifies what would be required for this).

[2] Additional P removal by dosing metal salts in the water line is theoretically possible everywhere and is not included as a co-benefit in this table.

[3] Outside the IPMV pilot, laboratory-scale research has been done with another zeolite that was not available during the pilot. That zeolite can remove both sulfamethoxazole and ammonium (see Doekhi-Bennani, 2021).

4.2.3 MITIGATION OF BROMATE FORMATION

Pilot studies with ozonation technologies in the IPMV found low bromate concentrations in the pilot effluents. This was also the case at very high influent bromide levels (e.g., approx. 1.5-2 mg bromide/l at WWWT Walcheren during the MicroForce pilot) or after artificially adding bromide to assess bromate formation (around 1 mg bromide/l in the O_3 + ultrasound pilot at WWTP Winterswijk).

Specific ozone dosages in the pilot installations ranged from 0.3 to 0.55 g O_3/g DOC. The pilot results are therefore in alignment with the 'Technical Guidelines on Oxidation Products in Ozonation' (STOWA 2022-48). These guidelines state that little to no bromate formation is expected at specific ozone dosages <0.6 g O_3/g DOC.

Beyond the influent bromide concentration, the required ozone dosage and method of ozone introduction play a crucial role in mitigating bromate formation. Indeed, the influent bromide concentration can hardly, if at all, be controlled. However, a low ozone dosage combined with fine-bubble diffusers greatly reduces the risk of bromate formation. The specific ozone dosage is dependent on the technology chosen and the required removal efficiency. The method of ozone introduction can, in general, be chosen freely, which leaves scope for optimisation.

In the O3-STEP pilot, bromate removal was observed in the post-treatment GAC filter under anoxic conditions, reducing concentrations to below the reporting limit of the measurement. For O3-STEP, at an ozone dosage of 0.4 g O_3/g DOC and an influent bromide concentration of 0.1-1 mg/l, bromate concentrations after ozonation ranged from below the reporting limit (with the lower bromide concentrations) to 2.3 µg/l (with the higher bromide concentrations).

4.2.4 ANTIBIOTIC RESISTANCE REMOVAL CO-BENEFITS (AMR: ANTIMICROBIAL RESISTANCE)

The extensive use of antibiotics in health care and livestock farming has led to the emergence of bacteria that is no longer responsive to antibiotics. These bacteria are referred to as antibiotic resistant. Resistant bacteria are found in hospital patients, among the general public, and in livestock and house pets. Susceptible organisms can become resistant to particular substances through mutation, by incorporating genetic elements that code for resistance into their DNA. Gene transfer tends to occur in systems with high densities of microorganisms, where suitable organisms are more likely to be in close proximity to one another. Antibiotic resistant bacteria are therefore also found in wastewater. Yet, wastewater treatment plants are insufficiently capable of removing these, making WWTP effluents an important source of antibiotic resistant bacteria and resistance-conferring genes in surface waters. Advanced treatment technologies may enable (partial) removal of resistant bacteria and resistance genes.

This is relevant because humans can be exposed to antibiotic-resistant bacteria in surface waters contaminated by effluent, for example, during recreation, irrigation or via food.

A number of the technologies investigated within the IPMV have the potential to remove antibiotic-resistant bacteria and/or resistance genes. Whether this actually happens was investigated through a monitoring campaign. Coordinated measurements were conducted at the various IPMV pilots and demonstration installations that were constructed under the first round of the incentive Scheme. The campaign's aim was to investigate removal of a specific group of antibiotic-resistant bacteria, the Extended Spectrum Beta-Lactase (ESBL) producers, as well as a selection of resistance genes. It also examined whether the removal of *Escherichia coli* (*E. coli*) could serve as an indicator for removal of ESBL bacteria. The results are briefly summarized below. For more details, see the STOWA research report on removal of antibiotic resistance through advanced treatment technologies (STOWA 2024-30).

The results of the monitoring campaign should be regarded as indicative and cannot be extrapolated directly to other locations. This is because only a limited number of sites were sampled with a small number of repetitions per technology/facility: the WWTPs were sampled 1 to 10 times, with each setting (like PAC dosis) being sampled only once or twice. Moreover, the presence of antibiotic resistance is known to fluctuate widely over time, depending on the source of these bacteria and genes.

From the results, the following conclusions can be drawn:

- Both ESBL bacteria and resistance genes are present in all WWTP effluents.
- *E. coli* numbers are about 2 log units higher than ESBL bacteria. This 2-log difference remains virtually unchanged after treatment, confirming that removal of *E. coli* as a good indicator for removal of ESBL bacteria.

- Adsorptive technologies (PAC, GAC and other materials) remove almost no ESBL or resistance genes.
- Oxidative technologies (ozonation) achieve some removal of ESBL (0.5-3 log) and resistance genes, depending on the contact time and dose. Higher ozone dosages yield a greater degree of removal, but results were not conclusive. MicroForce seems to achieve a slightly higher removal than the other ozonation technologies.
- The filtration technologies, AdOx and DEX filter, remove almost no ESBL bacteria and resistance genes.
- Nanofiltration appears promising, as it removes almost all ESBL bacteria. The effect of post-treatment UV/H_2O_2 is unclear, but it seems to remove resistance genes to some extent.

These findings confirm expectations regarding the technologies.

It is recommended that, when selecting an advanced treatment technology, effectiveness in removing antimicrobial resistance (both bacteria and genes) should be taken into account alongside other factors. It is also important that the entire WWTP effluent be treated with the technology. If only a partial stream is treated, the removal of a few log units will be cancelled out by the high numbers of ESBL in the untreated stream.

To verify these findings, more extensive monitoring of the different technologies is recommended.

4.2.5 PFAS REMOVAL CO-BENEFITS

PFAS (poly- and perfluoroalkyl substances) is an umbrella term for a group of thousands of artificially made fluorinated compounds. Research into PFAS has, until recently, focused on a few selected groups of fully fluorinated PFAS, including the well-known PFOS and PFOA. These PFAS are highly persistent, mobile and hardly biodegradable — and they are found everywhere in the environment. An important finding of STOWA research on PFAS at WWTPs (STOWA 2021-46) is that, at most WWTPs, more stable PFAS (such as PFOS and PFOA) leave the WWTP than enter it. The explanation for this is the presence of known and unknown degradable PFAS, so-called ‘precursors’, in the influent. These precursors, which are usually not analysed, are converted in the WWTP into stable PFAS, which are analysed. STOWA 2021-46 additionally concludes that PFAS with very short chain lengths, such as TFA, should receive more attention in future monitoring campaigns.

In principle, all of the technologies investigated within the IPMV could potentially remove PFAS and/or PFAS precursors. Whether this actually happens was assessed in a monitoring campaign conducted alongside the monitoring of antibiotic-resistant bacteria and resistance genes during various IPMV pilots and at demonstration installations that were constructed under the first round of the incentive Scheme. In addition to standard PFAS analysis, two relatively new methods were utilised: (1) analysis of very short PFAS chains and (2) a screening for total precursors called the Total Oxidisable Precursor (TOP) assay. The results are briefly summarized below. For more details, see the STOWA research report on PFAS removal using advanced treatment technologies (STOWA 2024-29).

The results of the monitoring campaign should be regarded as indicative and are not suitable for direct extrapolation to other locations. This is because of the limited number of sites sampled and the small number of repetitions per technology/facility: the WWTPs were

sampled 1 to 10 times, with each setting (like PAC dosis) being sampled only once or twice. Each WWTP differed in the extent and profile of PFAS loading in the influent. Consideration of these differences, termed the 'fingerprint', is important both to assess the effectiveness of advanced removal technologies and to translate the findings from the monitoring campaign to the conditions at other sites. After all, what does not enter the WWTP, does not have to be removed in the WWTP.

From the results, the following conclusions can be drawn:

- Total PFAS concentrations (30 substances) in conventional effluent ranged from 12 to 92 ng PFAS(30)/l in the investigated WWTPs. This falls within normal ranges for WWTP effluent.
- The WWTPs studied all had low to moderate PFAS loads (1.2 to 6.8 mg/IE/year).
- After advanced treatment, total PFAS levels ranged from 1.5 to 96 ng PFAS(30)/l.
- Most advanced removal techniques did not remove any PFAS.
- In some technologies, PFAS concentrations even increased, especially if PFAS precursors were present in the regular effluent.
- The filtration technologies — nanofiltration, AdOx and DEX filter — all removed PFAS to some extent, with nanofiltration with fine membranes being the most promising.
- The effect of oxidative technologies was inconsistent; decreased, no effect and increased concentrations was observed. Any increases and decreases that were measured remained slight.

These findings confirm expectations with regard to the technologies. Among the very short-chain PFAS, only the shortest (TFA and TFMS) were detected. TFA concentrations varied from 430 to 2,400 ng/l, which was much higher than for the other PFAS (max 40 ng/l). TFMS concentrations varied between 4.5 and 45 ng/l. None of the technologies was capable of removing TFA, including the adsorption and filtration technologies that did remove other PFAS. Ozonation seemed to cause a slight increase in concentrations, depending on the substances present in the influent. TOP analyses showed the presence of precursors at all WWTPs, with some having higher levels than others, sometimes much higher. Various adsorption technologies removed PFAS precursors. Removal of PFAS precursors by oxidative technologies was variable. At demonstration installations with oxidative technologies (ozonation in Houten and Ge(o)zond in Werverhoof) an increase in PFAS during advanced treatment was measured, apparently caused by unknown PFAS precursors in the regular effluent.

It is recommended that the presence of PFAS and PFAS precursors also be considered, alongside other factors, when selecting an advanced treatment technology. In particular, if many precursors are present, selection of an oxidative technology would be less suitable. To verify these findings, more extensive monitoring of the different technologies is recommended.

4.2.6 MICROPLASTICS REMOVAL CO-BENEFITS

Co-benefits in the form of microplastic removal was not a topic of research within the IPMV. It was therefore not investigated in the pilots. However, for NF + UV/H_2O_2 and O_3 + ceramic MF, it can be assumed that microplastics cannot pass through the membranes used.

4.2.7 EFFLUENT REUSE CO-BENEFITS

Membrane filtration is very suitable for upgrading WWTP effluent to a quality sufficient for high-value applications. After all, depending on pore size, the membrane physically retains all larger contaminants. Membrane filtration can therefore be used to upgrade WWTP effluent to industrial water or as a pretreatment step for the production of drinking water. This distinguishes it from the other technologies tested within the IPMV.

By combining membrane filtration, such as ultrafiltration or ceramic MF, with ozonation or UV/ H_2O_2, a combined technology can be created that also removes micropollutants to very low concentrations. Removal of micropollutants via membrane filtration should therefore be seen primarily as a co-benefit in technology applications targeting high-value effluent reuse.

5

TECHNOLOGY READINESS LEVEL (TRL)

During the IPMV, the TRL levels of the investigated technologies were increased by the pilot studies. As of late 2023, the technologies could be divided into two TRL groups:

- Technologies ready to be applied now, or within a few years, at demonstration or full scale at a WWTP, with the main issues still to be addressed relating optimisation and scale-up (Table 5.1).
- Technologies requiring further research, because beyond optimisation and scale-up, knowledge gaps on their functioning remain that were not (fully) addressed within the IPMV. This was due, among other things, to problems with AdOX and DEX filter pilot installations and because of time constraints in the O_3 + ultrasound pilot. Table 5.2 lists the technologies for which further study is needed.

TABLE 5.1 TECHNOLOGY READINESS LEVEL (TRL) AND OUTSTANDING RESEARCH QUESTIONS (OPTIMISATION AND SCALE-UP)

Removal mechanism and technology	TRL	Research questions for optimisation and scale-up
Adsorption onto PAC		
PACAS reference	9	
PAC + cloth filtration	7	How does the technology perform under increased sludge loading combined with increased hydraulic loading? Is there an alternative to the required polymer dosing (for effective sludge/water separation)?
PACAS Nereda	8	Key issues: - Properties and quality controls of the PAC - Availability of sustainable PAC - Uncertainty regarding necessary ATEX measures to be taken for storage and dosing at the WWTP - Accurate measurement of powdered PAC washout into the effluent - When effluent is used; availability throughout the day and filtration
PAC +O_3	7-8	Optimum combination of PAC and ozone dosage to meet EU target (80%), mitigation of bromate formation, costs and sustainability
Adsorption onto GAC		
GAC reference	9	
O3-STEP (without N and P removal)	8	More extensive monitoring and optimisation in full-scale applications can lead to a further extension of service life, reducing operating costs and CO_2 footprint; more insight into bromate formation/removal in O3-STEP and advanced nutrient removal
Continuous upflow GAC	8	For the CarboPlus installation, more research is needed into backwash water use, the operation of automatic carbon dosing and impact at other WWTP sites. For DynaCarbon, further research is needed on pretreatment requirements, residence time and GAC service life
BODAC	6-7	The pressure filtration and oxygen dosing have a significant effect on the costs of BODAC applications. At WWTP Emmen, where the technology is applied as post-treatment, oxygen dosing is required due to high ammonium levels in the effluent. At WWTPs with lower ammonium concentrations in the effluent, air dosing alone may be sufficient. Further research is recommended in this regard, if possible including studies to further optimise oxygen dosing. In addition, a follow-up study is gaining experience with dosing iron into the filter influent, so that phosphate is bound and removed within the filter. With this 'add on', BOCAC can simultaneously nitrify, remove phosphate and degrade pharmaceutical residues
Continuous Bio-GAC + air	6-7	Pilot studies to advance micropollutant removal developments and extend the GAC service life
Aurea (BO_3)	6	GAC service life, necessity/effect of possible pretreatment, optimum O_3 dosage and percentage of backwash water

Removal mechanism and technology	TRL	Research questions for optimisation and scale-up
Oxidative and filtration technologies		
Ozonation reference	9	
O3-STEP (without N and P removal)	8	See above
PAC + O_3	7-8	See above
MicroForce	6	Service life of carrier material, nitrogen removal
Aurea (BO_3)	6	See above
O_3 + ceramic MF	6	Location and amount of H_2O_2 dosing relative to ozone dispersion systems for bromate mitigation and hydroxyl conversion of micropollutants; performance under stormwater (RWF) conditions (turbidity)

TABLE 5.2 TECHNOLOGY READINESS LEVEL (TRL) AND OUTSTANDING RESEARCH QUESTIONS (OPERATION AND NEW PILOT NEEDS)

Removal mechanism and technology	TRL	Research questions on operation and new pilot needs
Adsorption onto other non-fossil materials		
DEX filter	5	Concept still faces early-stage issues, such as backwashing; external regeneration not yet available; and DEXSORB remains expensive. Hydraulic optimisation is needed to prevent clogging, avoid media washout during backwash and extend service life to at least 20,000 BV
AdOx	5	First pilot was proof-of-principle; long-term pilot needed for stable operation before moving on to demonstration scale. Further research needed on: - Removal percentage during long adsorption-regeneration cycles - Strength of granules during longer-term use - Optimisation of regeneration process - Further development of (multiple types) zeolite granules - Improved drying before regeneration - More efficient ozone use through recirculation - Aligning zeolite column service life with EBCT
Oxidative and filtration technologies		
SF + UV/H_2O_2	5-6	Energy consumption is currently too high. Follow-up study demonstrates that both removal efficiency and energy consumption can be improved with a few optimisations. Further research is needed on means to further reduce energy demand, such as energy efficient UV lamps, more effective pretreatment, optimum reactor configuration, and causes of low UV transmittance.
O_3 + ultrasound	5	Large pilot was not continued, but energy consumption measurements would be valuable, as well as long-term testing with varying flows.
NF + UV/H_2O_2	5	NF and UV/H_2O_2 have each been applied at full scale in drinking water treatment, but not yet on WWTP effluent. How to deal with the concentrate stream?

6

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

6.1 SUMMARY: PERFORMANCE AND TRL

The findings from chapters 4 and 5 are summarized in Table 6.1. The table brings together all of the technologies, including the references, showing the removal efficiencies for 7/11 indicator substances, the CO_2 footprint per m^3 and costs per m^3 expressed as a range over the entire WWTP, as well as technology co-benefits (e.g., nutrient removal) and the TRL.

Note that the ranges in the table provide an indication of costs per m^3 over the total influent of the standard 100,000 PE WWTP. In practice, costs might be higher due to site- or project-specific circumstances.

TABLE 6.1 SUMMARY TABLE WITH REMOVAL EFFICIENCY, CO_2 FOOTPRINT, INDICATIVE COSTS, CO-BENEFITS AND TRL FOR STANDARD 100,000 PE WWTP IN 2024

Technology	Overall efficiency 7/11 (%)	CO_2 (g CO_2/m^3 $_{WWTP\ influent}$)	Costs (€/m^3 $_{WWTP\ influent}$)	Co-benefits[3]	TRL
PACAS reference	80-85	184	0.08 - 0.12		9
GAC reference	80-85	253	0.18 - 0.26		9
Ozonation reference	80-85	77	0.08 - 0.12		9
PAC + cloth filtration	approx. 80	135	0.17 - 0.25	P removal possible	7
PACAS Nereda	80-85 (84)	195	0.10 - 0.14		8
BODAC	approx. 80	81	0.14 - 0.22	NH_4 removal, P removal possible	6-7
Bio-GAC	approx. 80	50	0.12 - 0.18	NH_4 removal, P removal possible	6-7
O3-STEP (without N + P removal)	approx. 80	125	0.17 - 0.25	NO_3 and P removal possible	8
UpflowGAC - CarboPlus	80-85	161	0.14 - 0.20	P removal possible	8
UpflowGAC - DynaCarbon	80-85	187	0.20 - 0.30	P removal possible	8
SF+UV/H_2O_2	75-80	574	0.49 – 0.74	NO_3 and P removal possible	5-6
O_3 + ultrasound	85-90	74	0.08 - 0.12		5
PAC + O_3	approx. 85	144	0.14 - 0.22		7-8
MicroForce	> 80	69	0.17 - 0.25	NH_4 removal	6
Aurea (BO_3)	approx. 85	66	0.13 - 0.19	NH_4 removal, P removal possible	6
DEX filter	80-85	135	0.19 - 0.29	NH_4, NO_3 and P removal possible[2]	5
AdOx	approx. 75[1]	71	0.12 - 0.18		5
NF + UV/H_2O_2	85-90	183	0.36 - 0.54	High-value effluent reuse possible, P removal	5
O_3 + ceramicMF	approx. 80	167	0.50 - 0.76	High-value effluent reuse possible	6

[1] Assumption was 70% for 100,000 PE WWTP. If a larger fraction of the total WWTP flow is treated, the total efficiency would also be higher. Research on this technology is in progress.

[2] Further research into the mechanism is needed.

[3] Nutrient co-benefits are in some cases indicated as 'possible'. This refers to the addition of chemicals in post-treatment. Introducing (additional) metal salts in the water line is outside the scope of this analysis; only dosing in the post-treatment technology to achieve enhanced phosphorus removal is considered here.

6.2 DISCUSSION

This evaluation sought to compare the different technologies as fairly as possible, while also pinpointing their differences. It draws on findings from pilot installations as well as information from recently completed reference projects. To better understand the effect of a number of key parameters, sensitivity analyses were carried out.

That said, the selection and design of a micropollutant removal installation must always be tailored to, and evaluated on, a site-specific basis. Both the Dutch incentive scheme and the revised EU Urban Wastewater Directive require a removal efficiency of 80% in every sample, calculated as the difference between total influent and effluent (this was 70% in the first tranche of the contribution scheme). Within the IPMV, removal efficiency was calculated as an annual average. For the current evaluation, it was set at 80%, and a 40% annual average removal efficiency is assumed for the WWTP itself. In practice, a WWTP's total removal efficiency depends on a number of factors, including:

- Removal efficiency of the WWTP at a given point in time (seasonal variation)
- The share of sewerage water treated with a technology
- The ratio of stormwater (RWF) to dry weather flow (DWF) in the influent and how DWF is defined (sampling during DWF)
- Concentrations of micropollutants, DOC and suspended solids in the influent
- The extent to which the 7/11 indicator substances best removed in the WWTP overlap with those of the post-treatment technology

The figures presented in this study should therefore be considered indicative. In the coming years, more information will become available on the removal efficiencies of the technologies, both stand-alone and combined. In the Netherlands, up to now these have only been tested at full of demonstration scale for short periods of time or via the IPMV pilot studies. The removal efficiencies ultimately achieved may turn out to be better, but they could also be worse.

The estimated costs of the technologies provides a snapshot; actual expenditures will vary due to market dynamics, method of procurement and site-specific circumstances.

In practice, each WWTP will have to carry out a site-specific assessment. Implementing a PACAS system, for example, does not contribute to nutrient removal, though it may be required if a WWTP is faced with tighter discharge standards under the Water Framework Directive (WFD). Moreover, any additional treatment step has to fit within the WWTP's hydraulic line, the available capacity of the electrical grid and influent bromide concentrations. Another important question is whether a single technology can realistically achieve the micropollutant removal required at a given WWTP, or whether a combination of technologies would be better suited to achieve the micropollutant removal efficiency required (according to the IPMV protocol and the EU Directive). Making this determination requires knowledge of micropollutant concentrations in the influent and effluent, as well as the WWTP's current performance and the DWF/RWF ratio.

Furthermore, in the coming year the Directive on Priority Substances is due to be updated, in which one or more pharmaceutical residue is expected to be assigned as regulatory discharge requirements. This means that, in addition to the EU Urban Wastewater Directive's stipulation of an overall removal efficiency across multiple indicator substances, individual substances may also carry specific discharge requirements. Whether, and to what extent, a

given technology can remove such substances will then become a consideration in technology selection and/or design specifications.

Beyond the required removal efficiency, sustainability considerations are also important. Direct nanofiltration does not immediately emerge from this study as a cost-effective option with a low CO_2 footprint, but the technology is capable of upgrading effluent to a high-value quality that can be used locally as process water or further polished to drinking water. Given the growing demand for clean water, this may well become an important consideration.

Another important sustainability-related aspect is the development of sustainable PAC and GAC. In particular, sustainable PAC could lead to a significantly lower CO_2 footprint for this raw material. Availability, cost and an understanding of the CO_2 footprint of non-fossil PAC will therefore remain essential.

Another critical site-specific consideration is the availability of a sufficiently large power connection and/or enough grid capacity. Where grid capacity is limited, use of technologies with high power demand will not be feasible. In regard to ozonation technologies, energy use can be reduced by generating ozone from pure oxygen.

In the coming years, the Dutch water authorities will need to take decisions for particular WWTPs based on the micropollutant removal requirements set in the revised EU Directive. Each water authority will make its (own) choices, based on the necessary removal efficiencies, costs, CO_2 footprint, grid connection availability, consumption of process additives, space requirements, TRL and other individual priorities and objectives. The design assumptions, criteria, co-benefits and TRL levels outlined in this evaluation, together with operational experience gained in demonstration and full-scale projects still to be developed, will provide important inputs for these decisions.

6.3 CONCLUSIONS

Within the IPMV, many technologies were developed and advanced to technological maturity (higher TRLs) within a relatively short periods of time. The water authorities therefore now have something to choose from.

Several technologies still require further research: DEX filter, AdOx, NF + UV/H_2O_2, O_3 + ultrasound and SF + UV/H_2O_2. For these technologies, open research questions remain or optimisations are needed before they can be applied at full WWTP scale. The same holds for membrane-based technologies.

An annual removal efficiency of 80% for 7/11 indicator substances over the entire WWTP can theoretically be achieved with all of the tested technologies. This will always, however, depend on the characteristics of a particular WWTP. It is therefore necessary to take the local context into account when selecting a technology.

Depending on the removal mechanisms combined, technology combinations can yield a higher removal of more substances compared to a stand-alone technology. But this will not be the case for every combination. Combined technologies can also provide greater flexibility in meeting discharge requirements and/or reducing the CO_2 footprint, because they provide more parameters that can be adjusted. When biological removal is low, a sufficiently robust

technology design can make it easier to nonetheless meet the required removal efficiency. However, this comes at a cost, as combined technologies generally involve higher foundation costs compared to a stand-alone technology. Two of the combined technologies, Aurea (BO_3) and MicroForce, offer the additional advantage of a low CO_2 footprint.

That said, stand-alone technologies offer several advantages: PACAS has the lowest foundation costs and, together with ozonation, the lowest costs per m^3; ozonation, BODAC and Bio-GAC score best on CO_2 footprint and in this regard are comparable to the two combined technologies, Aurea (BO_3) and MicroForce, mentioned above. For ozonation, the required micropollutant removal efficiency can be achieved at a relatively low cost and with a relatively small CO_2 footprint.

During the IPMV, considerable experience was gained on the possibilities and limitations of mitigating bromate formation. In addition to influent bromide concentration, the necessary ozone dosage and method of dosing play an important role in preventing bromate formation. A low ozone dosage combined with fine-bubble diffusers greatly reduces the risk of bromate formation. For O3-STEP specifically, bromate formed during ozonation was reduced under anoxic conditions in the GAC filter.

The development of BACF (BODAC, bio-GAC+air and Aurea (BO_3)) for advanced removal of micropollutants is a key outcome of the IPMV. BACF offers the possibility to apply a GAC filter with a low CO_2 footprint and at low operating cost, as long as the GAC does in fact last 15 years in actual practice. This still needs to be confirmed under operational conditions. Depending on conditions at a given WWTP, BACF can be utilised as a stand-alone technology (BODAC, Bio-GAC + air) or combined with ozonation (Aurea (BO_3)), in which case ozone consumption is greatly reduced.

The MicroForce concept, which uses HDPE carrier material instead of granular carbon, is also promising because its low ozone consumption combined with biological degradation results in low costs per m^3 and a low CO_2 footprint.

The sensitivity analysis demonstrated that the influence of sustainability measures, such as ‘green’ (renewable) electricity and sustainable PAC, can improve the CO_2 footprint of certain technologies to such an extent that their relative ranking changes.

In addition to pharmaceuticals, some technologies can also remove other substances, such as nutrients. Given the major Water Framework Directive challenges ahead, this provides opportunities for synergies and linked objectives and may motivate the selection of a specific technology or combination of technologies as an alternative to, or in addition to, optimising nutrient removal in the main treatment line.

Membrane filtration technologies combined with an oxidation step are suitable for combining high-value effluent reuse objectives with micropollutant removal. At WWTPs where high-value effluent reuse is a priority, micropollutant removal can be achieved relatively easily at the same time.

6.4 RECOMMENDATIONS

Every WWTP has its own characteristics. For that reason, each will need to use the tool and methodology from STOWA 2020-06 to arrive at an appropriate design. DWF patterns and RWF/DWF ratios are site-specific. A DWF pattern may be more compressed if there is, for example, a long supply system with pressure pipes and/or misconnected inflow into the collecting system. These factors also determine how stormwater is conveyed: in pulses, as in gravity systems, or more gradually, as in a supply system with pressure pipes. It is therefore recommended to determine what hydraulic design capacity is needed and what annual flow should be treated for each WWTP.

As each WWTP location is unique, it is recommended that the choice of technology be based on a tailored multicriteria assessment. In that assessment, a range of criteria need to be weighed, such as costs, CO_2 footprint, available electricity connection, process additives/chemicals, space constraints, required removal efficiency, flexibility, and removal of nutrients and other co-benefits, as well as individual standards from the Directive on Priority Substances. Weighing these factors makes it possible to determine the technology best suited to a given location and aligned with the policy goals and other objectives of the water authority.

As a practical recommendation, it is important to monitor the removal efficiency of biological removal throughout the year. This is the only way to obtain certainty about the removal efficiency year-round of micropollutants. During winter, biological efficiency can drop. Moreover, depending on the TRL of the technology being considered, it is recommended that targeted tests be conducted and, if necessary, a pilot be carried out prior to full-scale implementation.

DEX filter, AdOx, NF + UV/H_2O_2, O_3 + ceramic MF and SF + UV/H_2O_2 warrant further study. For these technologies, outstanding research questions remain or optimisations are needed before they can be applied at a WWTP. Direct nanofiltration, in particular, shows strong potential for high-value reuse of WWTP effluent.

7

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The STOWA IPMV reports used can be found in appendix 1; they are not included in this bibliography.

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Mulder, M., 2022, Berekening CO_2 voetafdruk en kosten voor vergaande verwijdering van micro's uit rwzi-afvalwater; Ten behoeve van de bijdrageregeling 'Zuivering Medicijnresten' van het Ministerie van IenW, d.d. 21-12-2022

Mulder, M. 2023. Paragraaf EU gidsstoffen IPMV versie 4823.docx

STOWA 2012-06, GER-waarden en milieu-impactscores productie van hulpstoffen in de waterketen

STOWA 2015-27, Verwijdering van microverontreinigingen uit effluenten van rwzi's; een vertaling van kennis en ervaring uit Duitsland en Zwitserland.

STOWA 2018-02, PACAS — poederkooldosering in actiefslib voor verwijdering van microverontreinigingen; onderzoek naar effectiviteit en efficiëntie op de RWZI Papendrecht.

STOWA 2021-46, PFAS in influent, effluent en zuiveringsslib; resultaten van een meetcampagne op acht rwzi's.

Excel tool: 'Voorbeeldversie webtool STOWA 2020-06 standaard rwzi' ingevuld voor de IPMV standaard rwzi van 100.000 ie'

APPENDIX 1

IPMV STUDIES AND RESEARCH

	Feasibility study reports	Pilot study reports*
Powdered activated carbon (PAC)		
Powdered activated carbon combined with cloth filtration (Vinkel)	2020-21	2022-45
PACAS Nereda (Simpelveld)	2020-20	2023-02
PACAS combined with dosing of iron compounds	2021-37	
Sustainable alternative PACs for PACAS	2020-19	
Laboratory tests of sustainable alternatives to activated carbon	2021-24	
Granular activated carbon (GAC)		
Biological oxygen-dosed activated carbon (BODAC) (Emmen)	2020-46	2023-50
Continuous Bio-GAC + air (Emmen)	2022-11	2023-51
O3-STEP (Horstermeer)	2020-18	2023-43
Continuous Upflow µGAC + air (Hapert)	2021-36	2023-52
ARVIA	2020-17	
Oxidative technologies		
Ozonation and UV (Aarle Rixtel)		2022-41
Ultrasound USONiQ (Winterswijk)	2020-24	2023-30
PAC + O_3 (Leiden)	2020-23	2023-44
MicroForce; O_3 biofilm (Walcheren)	2022-14	2023-49
BO_3; biological pretreatment with O_3 (Horstermeer)	2022-41	2023-48
Alternative adsorbents		
Cyclodextrins, DEXSORB, Dex filter (Lelystad)	2021-38	2023-54
AdOx, zeolite with filtration (Leiden-Noord)	2022-10	2023-56
Zeolites in cleaning agents	2022-32	
Sand filters	2022-56	
Filtration		
PHAREM filtration system	2021-59	
Nanofiltration (Asten)	2020-22	2023-53
Water factory; pretreatment – nanofiltration (Wilp)		2023-47
Water factory: ozonation with ceramic microfiltration (Wervershoof)	2020-25	2023-46
Natural systems		
Natural systems	2022-42	
Other studies		
Measurement of powdered carbon in effluent	2023-32	
Review of the literature on oxidation products	2022-47	
Technical guidelines on oxidation products in ozonation	2022-48	
Release of micropollutants during digestion of sewage sludge with PAC	2023-31	
Effects of powdered carbon in sludge	2023-34	
Robust sampling methods for WWTPs to determine removal efficiencies of organic micropollutants	2023-45	
Removal of PFAS by advanced treatment techniques	2024-29	
Removal of antibiotic resistance by advanced treatment techniques	2024-30	

* The pilot studies shaded in light green are included in the current evaluation

APPENDIX 2

STANDARD 100,000 PE WWTP AT 150 G COD

The standard 100,000 PE WWTP at 150 g COD was defined to correspond with the WWTP initially elaborated for the IPMV (Mulder 2022). Consequently, the standard WWTP in 2024 is set to be equivalent to that at the start of the IPMV in 2018.

Influent and effluent

For the advanced removal of micropollutants, wastewater volumes and current effluent quality are key factors. These parameters are presented in the table below.

TABLE B2-1 **INFLUENT FLOW AND COMPOSITION OF THE STANDARD WWTP**

Parameter	Unit	
WWTP capacity	PE 150 g COD	100,000
Average daily flow rate (Q24)	m^3/d	21,000
Total annual flow rate	m^3/y	7,665,000
DWF peak	m^3/h	900
DWF design peak	m^3/h	1,040
Minimum hydraulic capacity post-treatment	m^3/h	1,040
Influent loads		
COD	kg/d	11,000
BOD	kg/d	4,400
Total P	kg/d	160
Kjeldahl N	kg/d	1,000
Suspended solids	kg/d	5,200

TABLE B2-2 **EFFLUENT REQUIREMENTS, STANDARD WWTP**

Parameter*	Unit	Effluent requirement
Total N (annual average)	mg N/l	≤10
Total P (annual average)	mg P/l	≤1
BOD (max*)	mg/l	≤20
COD (max*)	mg/l	≤125
Suspended solids (annual average/max*)	mg/l	≤10/ ≤30
NH_4-N (annual average/ max*)	mg N/l	≤1.5/ ≤3
DOC (min/average/max)	mg/l	7 / 11 / 18

* maximum value in every effluent sample.

DOC

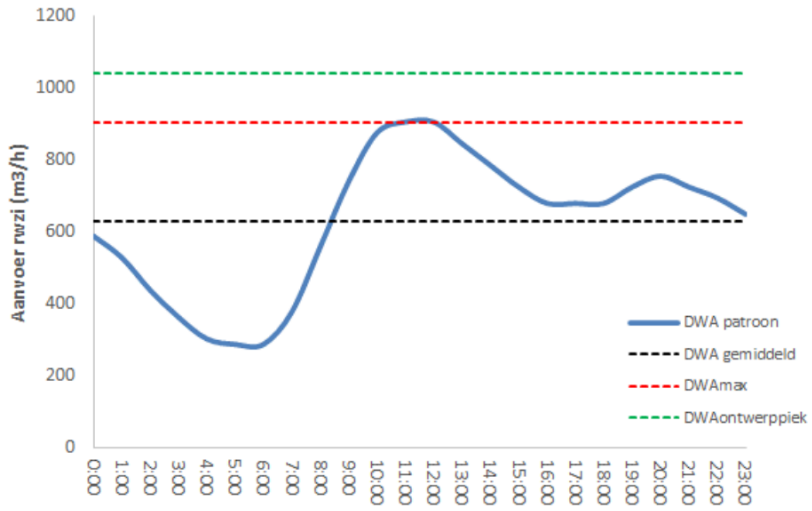
An key effluent quality parameter is the dissolved organic matter in the effluent, expressed as DOC (dissolved organic carbon). The DOC value of WWTP effluent is determined by passing a sample through a 0.45 µm filter. The fraction of organic matter not retained by the filter is referred to as the DOC. DOC levels in effluents of treatment plants in Western Europe typically range between 7 and 20 mg/l. DOC consists mainly of biopolymers (including extracellular bacterial polymers), proteins, sugars, humic acids and other dissolved organic compounds such as micropollutants. The higher the DOC concentration, the more ozone or activated carbon must be dosed to achieve the same level of micropollutant removal. Based on measured DOC values in WWTP effluents up to and including 2018, a DOC concentration of 11 mg/l was selected as the IPMV standard with a range of 7 to 18 mg/l.

DWF pattern

Within the IPMV, a standard DWF pattern was used, derived from STOWA 2015-27 (see Figure B2-1). This DWF pattern is based on hourly flows averaged over a period of one to three years under dry weather conditions. Consequently, there is a variability of about 15% in the pattern shown in Figure B2-1. The capacity of any post-treatment installation should at least match the DWF design peak of 1,040 m^3/h, as shown in the figure.

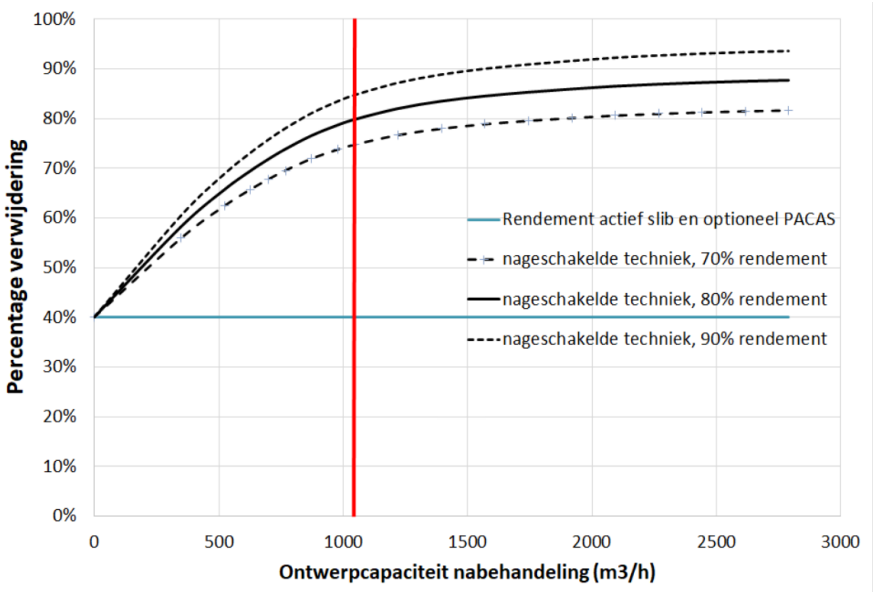
At this capacity, dry weather flow can always be treated. During rainfall, the installation can operate at full capacity and treat the (diluted) influent up to the DWF design peak. With a RWF/DWF ratio of 3.5-6, this assumption implies that some 70-80% of the total annual wastewater influent can be treated.

FIGURE B2-1 **DWF PATTERN FOR STANDARD 100,000 PE WWTP (IPMV), BASED ON STOWA 2015-27**



According to the IPMV guidelines, the post-treatment installation must be designed for a DWF peak flow of at least 1,040 m^3/h (see Table B2-1). With this design flow, an overall annual removal efficiency of 85% can be achieved at 90% post-treatment efficiency. If post-treatment efficiency reaches no more than 80%, an overall annual removal efficiency of 80% can be achieved. These values were calculated using the Excel tool in STOWA 2020-06 based on the standard IPMV WWTP (Mulder 2022). Note: The calculations assume 40% activated sludge removal efficiency for 7/11 indicator substances.

FIGURE B2-2 **RESULTS FROM THE EXAMPLE VERSION OF THE STOWA 2020-06 WEB TOOL, STANDARD WWTP: THE RED LINE SHOWS THE INTERSECTIONS AT WHICH AN OVERALL ANNUAL REMOVAL EFFICIENCY OF 80-85% CAN BE ACHIEVED (80% AT 80% POST-TREATMENT, AND 85% AT 90% POST-TREATMENT); IN OTHER WORDS, WHICH DESIGN FLOW MUST BE SELECTED (APPROX. 1,040 M^3/H)**



Overige kentallen

TABLE B2-3 **OTHER REFERENCE VALUES, STANDARD WWTP**

Parameter	Unit	
Use of fossil fuels		
Natural gas purchased	Nm^3/y	3,710
Diesel purchased	kg/year	16,000
Electricity consumption aeration	kWh/kg O_2	3.0
Electricity consumption sludge dewatering	kWh/kg DS	0.06
Biogas production		
Digestion residence time	days	20
Digestion temperature	°C	32
Degradation of dry matter (mixed primary and secondary sludge)	%	30
Specific gas production	Nm^3/kg DS degraded	1.1
Conversion of biogas into combined heat and power (CHP)		
Flaring/venting/loss of biogas	%	8
Electrical efficiency CHP	%	35
Share of generated heat utilised (CHP)	%	50

APPENDIX 3

OCALCULATION OF CO_2 FOOTPRINT

- The CO_2 footprint of utilised materials is divided over their total service life (15-30 years). For many materials, this results in a CO_2 impact of less than 0.1% of the total annual CO_2 footprint of wastewater treatment. These materials were therefore omitted from the analysis. An exception is reinforced concrete, which can account for more than 1% of the CO_2 footprint and is therefore included in the footprint calculation. To calculate the contribution of reinforced concrete to the CO_2 footprint, values for post-treatment from STOWA 2015-27 were applied.
- Assumptions for the CO_2 emission factors pertaining to chemicals and process additives are based on STOWA 2012-06. In that report, the energetic impact of chemicals and additives is expressed in primary energy. Since more than 95-99% of the CO_2 footprint of chemicals and additives is determined by fossil energy, the footprint per unit is calculated using the conversion factor from Table 2.3.
- As in 2018, fossil-based electricity was assumed; the model does not consider the use of wind turbines, solar panels, geothermal energy, residual heat, etc. This is, first, because renewable energy with lower CO_2 emission per unit can only be assumed if it is actually generated and used at the WWTP site itself. Paper-based offsets, such as the purchase of green certificates or CO2 rights from abroad, do not count. This means that the energy demand for wastewater treatment must in actual practice be generated locally in the Netherlands. At present, it is not possible or feasible to meet the electricity demand for wastewater treatment entirely with renewable electricity locally generated in the Netherlands. Adding supplementary treatment to remove micropollutants requires even more energy (approx. 40% increase). Given this significant increase and the inability to meet current energy demand with power locally generated in the Netherlands, it was decided to assume CO_2 emissions from fossil sources for all energy carriers (electricity, natural gas, coal, oil, gasoline, etc.).
- This also means that the energy demanded for the supplementary technologies cannot be offset against renewable generation of energy. The same applies to suppliers of process additives and chemicals: offsets for the use of renewable energy in the production of these inputs are not permitted.

TABLE 7.1 **GROSS ENERGY REQUIREMENT (GER) VALUES AND CO_2 EMISSION FACTORS FOR PROCESS ADDITIVES**

Parameter	Unit	Value
Activated carbon	MJ/kg	164
Regenerated activated carbon	MJ/kg	43.1
Activated carbon of biological origin (41% of fresh)	MJ/kg	67.2
Aluminium chloride	MJ/kg	14.90
Aluminium sulphate	MJ/kg	9.40
Ferric chloride	MJ/kg	16.30
Ferric chlorosulphate	MJ/kg	12.30
Ferrous sulphate	MJ/kg	3.40
Magnesium chloride, 54% solution	MJ/kg	2.10
Magnesium chloride, anhydrous	MJ/kg	23.60
Magnesium chloride, hydrate, solid form	MJ/kg	3.30
Magnesium oxide	MJ/kg	2.80
Methanol	MJ/kg	37.6
Sodium aluminate, 38% dry matter	MJ/kg	21.30
Sodium hypochlorite	MJ/kg	17.50
Polyaluminium chloride	MJ/kg	19.45
Polyaluminium sulphate	MJ/kg	17.30
Other metal salts	MJ/kg	15.70
Polyacrylamide homopolymer, nonionic, powder, 99% pure	kg CO_2/kg	3.36
Polyacrylamide, anionic, powder, 99% pure	kg CO_2/kg	3.06
Polyacrylamide, anionic, liquid, emulsion 50%	kg CO_2/kg	2.06
Polyacrylamide, cationic, powder, 99% pure	kg CO_2/kg	3.56
Polyacrylamide, cationic, liquid, emulsion 50%	kg CO_2/kg	2.26
Hydrogen peroxide (50% in H_20)	MJ/kg	22.8
Oxygen (liquid)	MJ/kg	8.8

Source: STOWA 2012-06 (Polymeren: Klimaatmonitor 2022, hulpstoffen).

APPENDIX 4

CCRITERIA FOR REFERENCE TECHNOLOGIES, BASE YEAR 2018

TABLE 7.2 CRITERIA FOR REFERENCE TECHNOLOGIES (BASE YEAR 2018)*

Criterion	Unit	PACAS	Ozonation	Ozonation + SF	GAC****
CO_2 footprint					
CO_2 footprint micropollutant removal	g CO_2/m^3 treated	122	98	128	325
CO_2 footprint micropollutant removal	g CO_2/m^3 WWTP influent*	122	69	90	228
Costs					
Annual costs	€/m^3 treated	0.06	0.13	0.17	0.26
Annual costs	€/m^3 WWTP influent*	0.06	0.09	0.12	0.18
Removal efficiency indicator substances, Dutch Ministry of Infrastructure and Water Management (Min I&W)**					
Technology removal efficiency	%	70-75	80-90	80-90	80-90
Removal efficiency including WWTP***	%	70-75	80-85	80-85	80-85

* Per m^3 of treated wastewater, i.e. the total costs or CO_2 emissions for application of the supplementary technology divided by the number of treated m^3. For PACAS, all incoming wastewater is treated (technology integrated in the activated sludge system). For post-treatment technologies (ozonation, ozonation + sand filter and GAC filter), at least the daily dry-weather design peak (DWF design peak) must always be treated and 70% of the annual flow (in which case removal efficiency in the treated stream must also be high).

** Removal efficiency for at least 7/11 indicator substances: benzotriazole, carbamazepine, diclofenac, irbesartan, gabapentin, metoprolol, hydrochlorothiazide, 4- and 5-methylbenzotriazole, sotalol, trimethoprim and venlafaxine, in each 24h or 48h flow- or time-proportional sample, accounting for 24h residence time of the water in the WWTP. These 11 indicator substances were selected to monitor the effectiveness of supplementary treatment for micropollutant removal from WWTP effluent and are not related to their potential environmental impact.

***Assumes 40% activated sludge efficiency for 7/11 indicator substances.

****Excluding nutrient removal.

APPENDIX 5

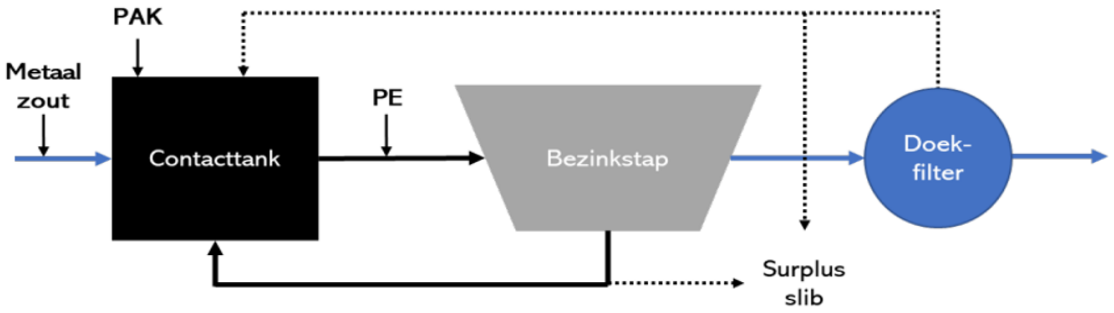
FACTSHEETS

TECHNOLOGY NAME: POWDERED ACTIVATED CARBON (PAC) COMBINED WITH CLOTH FILTRATION

Technology description

In PAC + cloth filtration powdered activated carbon (PAC) is dosed into the effluent of a WWTP in a contact tank. The PAC is then separated from the wastewater by a settling step and cloth filtration. Like other adsorption technologies, micropollutants are removed from the wastewater by adsorption onto activated carbon. Adding a coagulant enables advanced removal of phosphorus. Expected advantages compared to the reference are a lower PAC dose and enhanced P removal. In particular, the lower PAC consumption compared to PACAS gives PAC + cloth filtration a more favourable CO_2 footprint. The technology requires polymer (PE) and metal salt dosing.

Process integration schematic (block diagram)



Pilot installation as implemented within the IPMV		
Parameter	**Unit**	**Value**
WWTP location	-	Vinkel
Period	month/year – month/year	April 2021 – August 2021
Pilot installation capacity	m^3/h	1–5
Tested variations	e.g., dosage in mg PAC/l or g O_3/g DOC	5, 10 and 15 mg PAC/l
Continuous/batch testing	-	Continuous
Specific information: e.g., PAC type		Norit SAE Super (Cabot)
Analyses performed		Micropollutants, nitrogen and biological effects, P, Fe

Design assumptions for full-scale installation		
Parameter	**Unit**	**Value**
Powdered activated carbon (PAC, post-treatment)		
PAC adsorption step		
HRT – adsorption phase	min	30
Pumping head	m	2
PAC dosage	mg/l	10
Metal salt dosage	mg Fe^{3+}/l	5
Metal salt dosage	mol Fe/mol P to be removed	5
PE dosage	mg active polymer/l	0.4
Additional sludge to be removed	kg DS/m^3 treated	0.025
Settling step		
Settling velocity PAC + metal salt mixture	m/h	1.5-5
Lamella surface loading (spatial)	$m^3/m^2/h$	2.5 or 4
Backwash water		
Backwash water type	-	t.b.d.
Backwash flow	% of incoming flow	5

Energy consumption		
Total energy consumption incl. pumping and backwash	kWh/treated m^3	0.063
Minimum pumping head for the technology	m	2
Technology	kWh/y	0.018
Energy consumption 8 m pumping head	kWh/y	0.035
Energy consumption backwash	kWh/y	0.010

Technology design for 100,000 PE WWTP at 150 g COD		
Parameter	**Unit**	**Value**
Technology design		
Selected variant for design elaboration	-	Pilot design 4 and 5 with PAC dosing = 10 instead of 8
Design flow (technology)	m^3/h	1,040
Annual volume to be treated with the technology	m^3/year	5,365,500
Share of annual effluent treated	%	70
Powdered activated carbon (PAC, post-treatment)		
Pumping head	m	2
PAC dosage - nominal	kg/d	147
PAC dosage - max	kg/d	221
Metal salt dosage	kg Fe^{3+}/d	74
Design peak flow rate	m^3/h	1,040
PAC consumption	ton/y	54
Space requirement adsorption phase	m^2	200
Space requirement settling phase	m^2	260-420
Cloth filtration area	m^2	130
Space requirement cloth filters	m^2	50
Settling tank volume	m^3	
Settling tank depth	m	
Additional sludge removal	ton DS/y	134
Backwash water		
Backwash flow	m^3/h	268,275
Backwash time fraction	%	5%
Staffing		
Full time equivalents (FTE)	FTE/y	1
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/y	340,018
Minimum pumping head for technology	m	2
Technology	kWh/y	98,571
Energy consumption 8 m pumping head	kWh/y	187,793
Energy consumption backwash	kWh/y	53,655

Results based on IPMV criteria for 100,000 PE WWTP at 150 g COD		
		Updated
Parameter	**Unit**	**value 2024**
Removal efficiency micropollutants		
In substream (7/11 NL indicator substances)	%	92
In substream (11 NL indicator substances)	%	approx. 85
In full WWTP + post-treatment (7/11 NL indicator substances)	%	approx. 80
In substream (EU substances)	%	approx. 85
In full WWTP + post-treatment (EU substances)	%	75-80

CO_2 footprint		
CO_2 footprint	g CO_2/m^3 treated	193
CO_2 footprint	g CO_2/m^3 total WWTP	135
Costs (incl. VAT)		
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 treated	0.24-0.36
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 total WWTP	0.17-0.25
Ecotoxicity		
Ecotoxicity reduction	%	>50

Co-benefits		**updated**
Parameter	**Unit**	**Value 2024**
Additional total N removal	%	neutral
Additional total P removal	%	yes, depending on situation
Additional PFAS removal in technology	%	see STOWA 2024-29
Additional disinfection in technology (*E. coli* removal)	reduction factor (log)	neutral
Additional antibiotic resistant bacteria removal in technology	%	see STOWA 2024-30

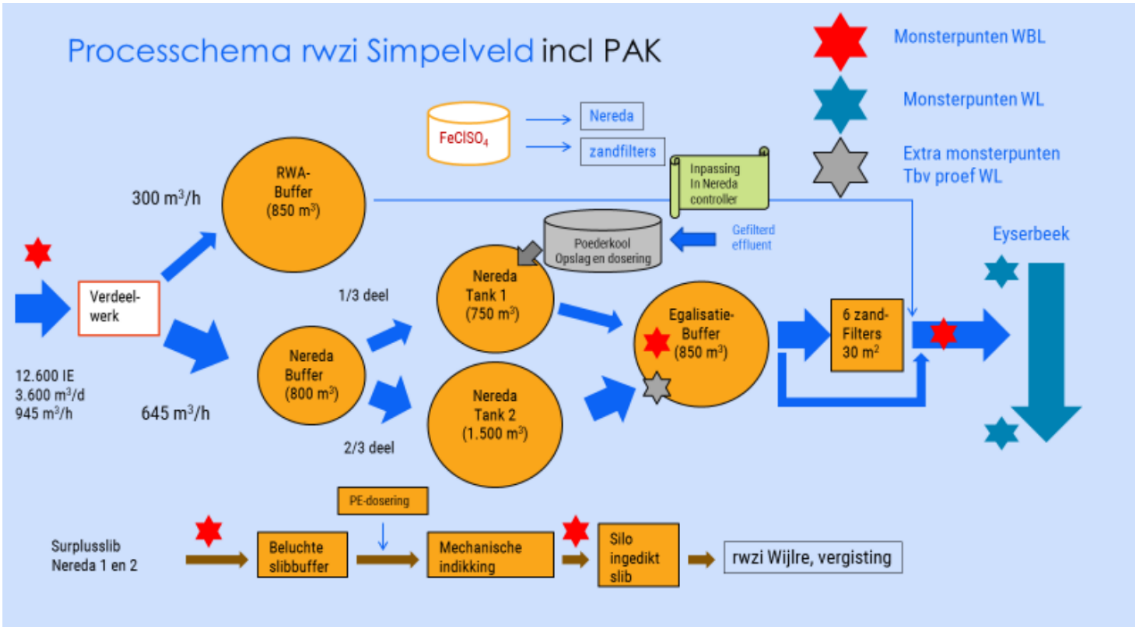
Technology readiness level (TRL)		
Parameter	**Unit**	**Value**
TRL		7
		PAC + cloth filtration is already being successfully applied at full scale in several WWTPs in Germany for the removal of micropollutants and advanced phosphorus removal.
Outstanding questions (scale-up)		How does the technology perform under increased sludge loading combined with increased hydraulic loading? Is there an alternative to the required polymer dosing (for effective sludge/water separation)?
Outstanding questions (optimisation and scale-up)		n.a.
Outstanding questions (operation / new pilot studies)		n.a.

TECHNOLOGY NAME: PACAS NEREDA

Technology description

Powdered activated carbon (PAC) dosing improves the removal of micropollutants and offers a relatively simple method for removing pharmaceutical residues in continuous-flow activated sludge systems. In PACAS Nereda, the PAC is dosed directly into a Nereda granular sludge reactor instead of a conventional activated sludge system. Pharmaceutical residues are bound onto the PAC and then removed together with the waste sludge via the regular sludge line (digesting, dewatering, drying and incineration).

Process integration schematic (block diagram)



Pilot installation as implemented within the IPMV		
Parameter	**Unit**	**Value**
WWTP location	**-**	**Simpelveld**
Period	month/year – month/year	April 2021 – June 2022
Pilot pretreatment		
Pilot installation capacity	m^3/h	215
Tested variations	e.g., dosage in mg PAC/l or g O_3/g DOC	5, 10, 15 and 20 mg PAC/l influent. First, fossil-derived PAC was tested, and in de final month a sustainable PAC was used (Acticarbone 2SW)
Continuous/batch testing	-	Batch (Nereda)
Some specific information: e.g., PAC type, 03 production from , bromide concentrations, DOC		PAC type: Pulsorb WP235
Analyses conducted		pharmaceutical residues, nutrients, macro-parameters, sludge composition, bioassays, PFAS, bromide and heavy metals

Design assumptions for full-scale installation		
Parameter	**Unit**	**Value**
PACAS		
PAC dosage - nominal	mg/l	20
PAC dosage - max	mg/l	20
Metal salt dosage	mg Fe^{3+}/l	0
Metal salt dosage	mol Fe/mol P to be removed	0

DS dewatered sludge without PAC (and any additional Fe)	% DS	6.4
DS dewatered sludge with PAC (and any additional Fe)	% DS	n.d.
Additional sludge to be removed	kg DS/m^3 treated	0,016
In combination with Nereda		
Cycle time	min	360
Dosing time	min/cycle	10
Dosing phase	-	Dosing phase of about 10 min per 6 hours. Calculated for each cycle (also accounting for RWF factor)
Energy consumption		
Total energy consumption of the technology	kWh/m^3 treated	0.030
Minimum pumping head for technology	m	0

Technology design for 100,000 PE WWTP at 150 g COD		
Parameter	**Unit**	**Value**
Technology design		
Selected variant for design elaboration	-	n.a. *
Design flow (technology)	m^3/h	1,500
Annual volume to be treated with the technology	m^3/year	7,665,000
Share of annual effluent treated	%	100
PACAS		
PAC dosage - nominal	kg/d	336
PAC dosage - max	kg/d	416
Metal salt dosage	kg Fe^{3+}/d	0
Moment of PAC addition in Nereda cycle	-	Dosing phase of about 10 min per 6 hours. Calculated for each cycle (also accounting for RWF factor) ** ***
Sludge production	ton DS/y	123
Staffing		
Full time equivalents (FTE)	FTE/y	0.5
Energy consumption		
Total energy consumption of the technology	kWh/y	230,000
Minimum pumping head for technology	m	0

Results based on IPMV criteria for 100,000 PE WWTP at 150 g COD		
		Updated
Parameter	**Unit**	**value 2024**
Removal efficiency micropollutants		
In substream (7/11 NL indicator substances)	%	n.a.
In substream (11 NL indicator substances)	%	n.a.
In full WWTP + post-treatment (7/11 NL indicator substances)	%	80-85 (pilot: 84)
In substream (EU substances)	%	n.a.
In full WWTP + post-treatment (EU substances)	%	75-85 (pilot: 85)
CO_2 footprint		
CO_2 footprint	g CO_2/m^3 treated	195
CO_2 footprint	g CO_2/m^3 total WWTP	195
Costs (incl. VAT)		
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 treated	0.10-0.15
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 total WWTP	0.10-0.15
Ecotoxicity		
Ecotoxicity reduction	%	

Co-benefits		**Updated**
Parameter	**Unit**	**value 2024**
Additional total N removal	%	neutral
Additional ammonium removal	%	neutral
Additional total P removal	%	neutral, additional removal possible with metal salt dosing
Additional PFAS removal in technology	%	see STOWA 2024-29
Additional disinfection in technology (*E. coli* removal)	reduction factor (log)	neutral
Additional antibiotic resistant bacteria removal in technology	%	see STOWA 2024-30

Technology readiness level (TRL)		
Parameter	**Unit**	**Value**
TRL		8
Outstanding questions (scale-up)		Key issues: - Carbon properties and quality control - Availability of sustainable carbon - Uncertainty regarding necessary ATEX measures to be taken for storage and dosing at the WWTP - Accurate measurement of PAC washout into the effluent - When effluent is reused: Availability throughout the day and filtration

* A Nereda installation with a capacity of 100,000 PE and average daily flow of 20,800 m^3/d typically consists of one buffer tank and two reactors of equal size. The Nereda reactors are alternately fed with influent and aerated. PAC is dosed
at the end of the aeration phase, so a single PAC dosing unit usually suffices.

** A new phase is introduced in the Nereda cycle: PAC dosing. PAC is dosed 30 minutes before the end of the aeration phase or when the ammonium concentration falls below 5 mg N/l. The amount of PAC per cycle is
calculated based on the target dose (g/m^3) and batch size (m^3).

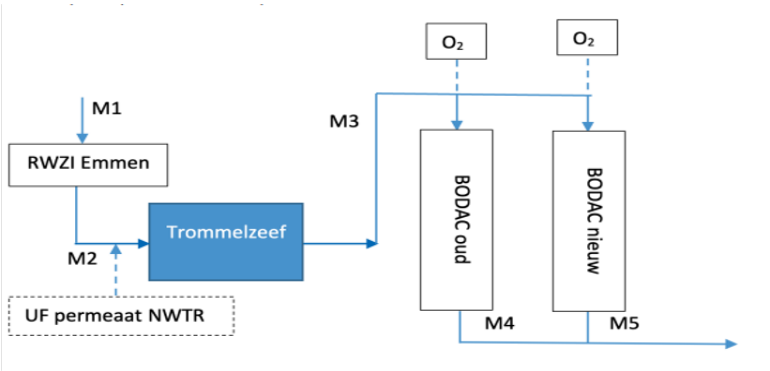
*** The Nereda® **cycle time is adjusted based on the** flow rate. The higher the flow rate the shorter the cycle. At a cycle time of 150 minutes or less (in RWF conditions), PAC dosage is reduced by 15%. Beyond 2x DWF, the dosing is not further increased.

TECHNOLOGY NAME: BIOLOGICAL OXYGEN-DOSED ACTIVATED CARBON (BODAC)

Technology description

A BODAC installation consists of two (activated carbon) filtration steps in series. Oxygen is dosed to the influent of both filtration steps to prevent anaerobic conditions inside the BODAC filters. Oxygen has to be added to meet the oxygen demand during biological filtration. In biological activated carbon filtration, a biofilm develops on and within the activated carbon. Over time, biodegradation becomes the dominant removal mechanism; adsorption plays little to no further role as the carbon becomes saturated. An expected advantage of the technology is a longer carbon service life compared to the GAC reference.

Process integration schematic (block diagram)



Pilot installation as implemented within the IPMV

Parameter	Unit	Value
WWTP location	-	(Emmen)
Period	month/year – month/year	May 2019 – May 2020
Pilot pretreatment		drum screen 50 µm
Pilot installation capacity	m^3/h	5
Tested variations	e.g., dosage in mg PAC/l or g O_3/g DOC	'old' and fresh activated carbon
Continuous/batch testing	-	Continuous
Some specific information: e.g., PAC type, O_3 production from air/O_2, bromide concentrations, DOC		Norit 830P
Analyses conducted		Macroparameters, micropollutants, bacteria, bioassays, non-target screening

Design assumptions for full-scale installation

Parameter	Unit	Value
Granular activated carbon (GAC)		
Oxygen dosage	mg O_2/l	20
Hydraulic loading	m/h	7
EBCT at DWF design peak	min	15 -30
EBCT at average flow	min	23
Residence time flocculation zone	s	n.a.
Required bed volume	m^3	1.25
Bed depth	m	2.5
Filtration rate at DWF design peak	m/h	5.4-10
Filtration rate, at average flow	m/h	7
Configuration (upflow/downflow)	-	Downflow
GAC type	-	Norit 830P
GAC granule size (diameter)	mm	0.6-2.36
Carbon service life	months	180
Carbon service life	bed volumes	201,206
Additional sludge to be removed	kg DS/m^3 treated	0.003

Prefiltration		
Filter type	-	ultrafiltration or drum screen
Pore size	µm	50
Backwash water		
Backwash water type	-	alternating with water and air
Backwash flow	% of incoming flow	1%=average, 10%=design
Frequency for all filters combined	number of times/h	once per 48 to 72 hours
Duration	min	8
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/m³ treated	0.14
Minimum pumping head for technology	m	22
Energy consumption for 22 m pumping head	kWh/m³ treated	0.10
Backwash energy consumption (1%)	kWh/m³ treated	0.002
Other energy consumption (incl. drum screen)	kWh/m³ treated	0.04

Technology design for 100,000 PE WWTP at 150 g COD		
Parameter	**Unit**	**Value**
Technology design		
Selected variant for design elaboration	-	n.a.
Design flow (technology)	m³/h	1,040
Annual volume to be treated with the technology	m³/year	5,365,500
Share of annual effluent treated	%	70
Granular activated carbon (GAC)		
Oxygen dosage	g O_2/h	20,800
Hydraulic loading	m/h	10
Required bed volume	m³	400
Bed depth	m	2,5
filter area	m²	11
Configuration (upflow/downflow)	-	Downflow
Number of filters		14
Total filter area	m²	160
GAC type	-	Norit 830P
GAC granule size (diameter)	mm	0.6-2.36
Carbon dosage	kg/d	n.a.
Additional sludge removal	ton DS/y	16
Prefiltration		
Filter type	-	UF or drum screen
Pore size	µm	50
Backwash water		
Backwash flow	m³/h	500
Backwash time fraction	%	0.40%
Frequency for all filters combined	number of times/h	once per 6 hours
Duration	min	20
Effluent storage time in buffer tank for backwash	h	0.5
Staffing		
Full time equivalents (FTE)	FTE/y	0.5
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/y	751,000
Minimum pumping head for technology	m	22
Energy consumption - 22 m pumping head	kWh/y	516,429

Backwash energy consumption (1%)	kWh/y	10,731
Other energy consumption (incl. drum screen)	kWh/y	223,840

Results based on IPMV criteria for 100,000 PE WWTP at 150 g COD		
		Updated
Parameter	**Unit**	**value 2024**
Removal efficiency micropollutants		
In substream (7/11 NL indicator substances)	%	> 80
In substream (11 NL indicator substances)	%	n.d.
In full WWTP + post-treatment (7/11 NL indicator substances)	%	approx. 80
In substream (EU substances)	%	75-85
In full WWTP + post-treatment (EU substances)	%	70-80
CO_2 footprint		
CO_2 footprint	g CO_2/m^3 treated	116
CO_2 footprint	g CO_2/m^3 total WWTP	81
Costs (incl. VAT)		
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 treated	0.20-0.30
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 total WWTP	0.14-0.21
Ecotoxicity		
Ecotoxicity reduction	%	50

Co-benefits		**updated**
Parameter	**Unit**	**Value 2024**
Additional total N removal	%	neutral
Additional ammonium removal	%	99
Ammonium concentration at technology inlet	mg N/l	2-12.5
Ammonium concentration at technology outlet	mg N/l	0-0.36
Additional total P removal	%	neutral, possible via DS capture or with additional metal salt dosing
Additional PFAS removal in technology	%	see STOWA 2024-29
Additional disinfection in technology (*E. coli* removal)	reduction factor (log)	neutral
Additional antibiotic resistant bacteria removal in technology	%	see STOWA 2024-30

Technology readiness level (TRL)		
Parameter	**Unit**	**Value**
TRL		6 to 7
		The pressure filtration and oxygen dosing have a significant effect on the costs of BODAC applications. For application as post-treatment at WWTP Emmen, oxygen dosing was required due to high ammonium concentrations in the effluent. At other WWTPs with lower effluent ammonium concentrations, air dosing alone may be sufficient. Experiences in this project suggest this is an area that should be further investigated. Additional research is also recommended on possible ways to optimise oxygen dosing.

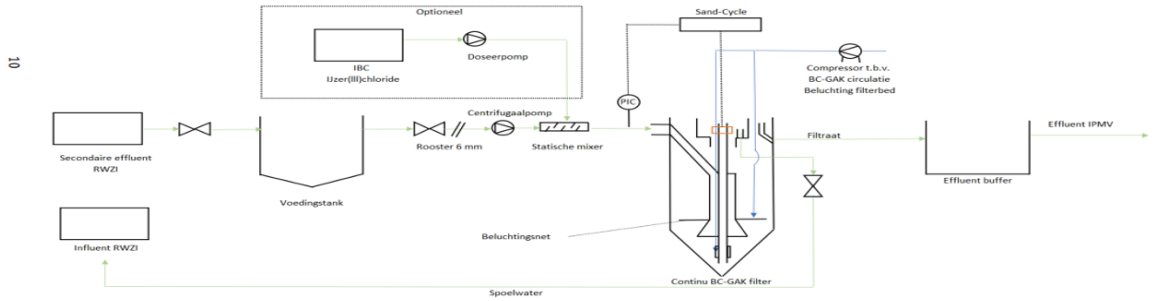
Outstanding questions (scale-up)		A follow-up study is planned to gain experience with dosing iron into the filter influent, so that phosphate is bound and captured in the filter. With this 'add on', BODAC could simultaneously nitrify, remove phosphate and degrade pharmaceutical residues.
Outstanding questions (optimisation and scale-up_		n.a.
Outstanding questions (operation / new pilot studies)		n.a.

TECHNOLOGY NAME: CONTINUOUS BIO-GAC + AIR

Technology description

In practical applications, continuous filtration has proven suitable as a 'bioreactor', with biological conversion occurring on and around the filter medium. The pilot investigated the concept of continuous filtration with a granular activated carbon filter bed for the removal of micropollutants. Aeration of the filter promotes biological growth, thereby extending the carbon service life. Before the effluent is fed into the reactor, pretreatment is carried out using a drum screen (from BODAC). Expected advantages are a longer carbon service life compared to the GAC reference and the possibility of post-treatment phosphorous removal. This requires dosing of metal salts.

Process integration schematic (block diagram)



Pilot installation as implemented within the IPMV		
Parameter	**Unit**	**Value**
WWTP location	-	Emmen
Period	month/year – month/year	June 2022 – September 2023, extended after completion of the IPMV report in consultation with the advisory group (5 water authorities)
Pilot pretreatment		Initially, an inline filter was used. Later a drum screen was applied with a 50 µm mesh as pilot pretreatment
Pilot installation capacity	m^3/h	3-4
Continuous/batch testing	-	Continuous
Some specific information: e.g., PAC type, O_3 production from air/O_2, bromide concentrations, DOC		Norit 830
Analyses conducted		Macroparameters, micropollutants, bacteria, bioassays, non-target screening

Design assumptions for full-scale installation		
Parameter	**Unit**	**Value**
Granular activated carbon (GAC)		
Oxygen dosage	mg O_2/l	30-50
Hydraulic loading	m/h	5.7
EBCT at DWF design peak	min	26
EBCT at average flow	min	37
Residence time flocculation zone	s	0
Required bed volume	m^3	1.7
Bed depth	m	3
Filtration rate at DWF design peak	m/h	7.4
Filtration rate, at average flow	m/h	4.9
Configuration (upflow/downflow)	-	Upflow
GAC type	-	Norit GAC 830 AF
GAC granule size (diameter)	mm	0.60-2.36

Carbon service life	Months	180
Carbon service life	bed volumes	216,000
Carbon granule density	kg/m^3	400
Metal salt dose	mol Fe/mol P to be removed	5 (only for P removal)
Methanol dose	mg/l	0
Additional sludge to be removed	kg DS/m^3 treated	0.003
Prefiltration		
Filter type	-	drum screen
Pore size	µm	50 µm
Suspended solids (SS) concentration at inlet	mg/l	n.a.
SS concentration at outlet	mg/l	n.a.
Backwash water		
Backwash flow	% of incoming flow	1%
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/m^3 treated	0.073
Minimum pumping head for technology	m	10
Compressed air energy	kWh/m^3 treated	0.029
Feed pumping energy	kWh/m^3 treated	0.044
Backwash energy	kWh/m^3 treated	0.002

Technology design for a 100,000 PE WWTP at 150 g COD		
Parameter	**Unit**	**Value**
Technology design		
Selected variant for design elaboration	-	n.a.
Design flow (technology)	m^3/h	1,040
Annual volume to be treated with the technology	m^3/year	6,130,000
Share of annual effluent treated	%	80
Granular activated carbon (GAC)		
Oxygen dosage	g O_2/h	28
Hydraulic loading	m/h	7.4
Required bed volume	m^3	430
Bed depth	m	3
Filter surface area	m^2	140
Configuration (upflow/downflow)	-	Upflow
Number of filters		3
Total filter area	m^2	165
GAC type	-	Norit 830
GAC granule size (diameter)	mm	0.60 - 2.36
Carbon granule density	kg/m^3	400
Metal salt dose	kg Fe^{3+}/d	0
Methanol dose	kg/d	n.a.
Additional sludge removal	ton DS/y	18
Prefiltration		
Filter type	-	step screen or equivalent
Pore size	µm	2000
SS concentration at inlet	mg/h	10 - 20
SS concentration at outlet	mg/h	5 - 15
Backwash water		
Backwash flow	m^3/h	50
Backwash time fraction	%	7.2
Frequency for all filters combined	number of times/h	Continuous

Staffing		
Full time equivalents (FTE)	FTE/y	0.5
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/y	458,736
Minimum pumping head for technology	m	10
Compressed air energy	kWh/y	178,201
Feed pumping energy	kWh/y	268,275
Backwash energy	kWh/y	12,260

Results based on IPMV criteria for 100,000 PE WWTP at 150 g COD		
		Updated
Parameter	**Unit**	**value 2024**
Removal efficiency micropollutants		
In substream (7/11 NL indicator substances)	%	80-85
In substream (11 NL indicator substances)	%	70-75
In full WWTP + post-treatment (7/11 NL indicator substances)	%	approx. 80
In substream (EU substances)	%	75-85
In full WWTP + post-treatment (EU substances)	%	75-80
CO_2 footprint		
CO_2 footprint	g CO_2/m^3 treated	62
CO_2 footprint	g CO_2/m^3 total WWTP	50
Costs (incl. VAT)		
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 treated	0.15-0.22
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 total WWTP	0.12-0.18
Ecotoxicity		
Ecotoxicity reduction	%	

Co-benefits		**Updated**
Parameter	**Unit**	**value 2024**
Additional total N removal	%	neutral
Additional ammonium removal	%	40-90
Additional total P removal	%	neutral, possible with metal salt dosing
Additional PFAS removal in technology	%	see STOWA 2024-29
Additional disinfection in technology (*E. coli* removal)	reduction factor (log)	neutral
Additional antibiotic resistant bacteria removal in technology	%	see STOWA 2024-30

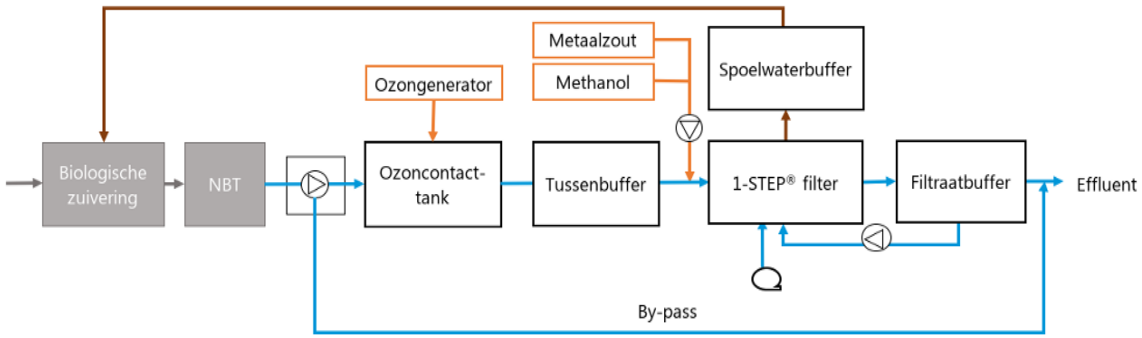
Technology Readiness Level (TRL)		
Parameter	**Unit**	**Value**
TRL		6 to 7
Outstanding questions (scale-up)		Pilot studies are further investigating micropollutant removal performance, along with extending the service life of the carbon filter
Outstanding questions (optimisation and scale-up)		n.a.
Outstanding questions (operation / new pilot studies)		n.a.

TECHNOLOGY NAME: O3-STEP

Technology description

The O3-STEP filter is a further evolution of the existing 1-STEP® filter technology in which post-treatment takes place via fixed-bed filtration with granular activated carbon serving as both the filtration and the adsorption medium. In the 1-STEP filter, several different processes occur: adsorption onto GAC, biological degradation, denitrification and phosphate removal by coagulation and flocculation, and filtration. The O3-STEP filter, adds an ozonation step to partially oxidise organic (micro) pollutants, including pharmaceutical residues. Expected advantages compared with the reference are a higher efficiency and broader-spectrum micropollutant removal efficiency, extended activated carbon service life, mitigation of bromate formation and a comparable (or slightly improved) CO_2 footprint and indicative costs. The technology requires dosing of methanol and metal salts.

Process integration schematic (block diagram)



If applied without nutrient removal (N and P) no metal salts or methanol dosing is used

Pilot installation as implemented within the IPMV

Parameter	Unit	Value
WWTP location	-	Horstermeer
Period	month/year – month/year	July 2021 – October 2022
Pilot pretreatment		n.a.
Pilot installation capacity	m^3/h	5 to 3
Tested variations	e.g., dosage in mg PAC/l or g O_3/g DOC	0.2-1 g O_3/g DOC
Continuous/batch testing	-	Continuous
Some specific information: e.g., PAC type, O_3 production from air/O_2, bromide levels, DOC		O_3 production from air with pressure swing adsorption (PSA), GAC 612 WFD
Analyses conducted		Macroparameters, micropollutants, bromide, bromate, bacteria, bioassays, non-target screening, metals

Design assumptions for full-scale installation

Parameter	Unit	Value	Value – incl. N and P
Oxidation with ozone and/or H_2O_2			
O_3 dosage - nominal	g O_3/g DOC	0.2 / 0.4	0.2 / 0.4
O_3 dosage - nominal (at 11 mg DOC/l)	g O_3/m^3	60-140	60-140
O_3 reactor contact time	min	10 - ...	10 - ...
O_3 reactor depth	m	5	5
O_3 input		diffusers	diffusers
H_2O_2	ppm	0	0

Granular activated carbon (GAC)			
Oxygen dosage	mg O_2/l	0	0
Hydraulic loading	m/h	10 to 15	10 to 15
EBCT at DWF design peak	min	10	10
EBCT at average flow	min	17	17
Residence time flocculation zone	s	432	432
Required bed volume	m^3	295	295
Bed depth	m	2.2	2.2
Filtration rate at DWF design peak	m/h	14	14
Filtration rate, at average flow	m/h	8	8
Configuration (upflow/downflow)	-	Downflow	Downflow
GAC type	-	GAC 612 WFD	GAC 612 WFD
GAC granule size (diameter)	mm	1.7-3.35	1.7-3.35
Carbon service life	Months	23	23
Carbon service life	bed volumes	>35000	>35000
Activated carbon granule density	kg/m^3	350-550	350-550
Metal salt dosage	mol Fe/mol P to be removed	n.a.	1-4
Methanol dosage	mg/l	n.a.	4 g methanol/g NO_x-N +1.2 g methanol/g O_2
Additional sludge to be removed	kg DS/m^3 treated	0	0.012
Energy consumption			
Total energy consumption for technology, incl. pumping and backwash	kWh/m^3 treated	0.12	0.13
Minimum pumping head for technology	m	4 - 6	4 - 6
Energy consumption per component - ozonation	kWh/m^3 treated	0.048	0.048
Energy consumption per component - 1-STEP	kWh/m^3 treated	0.030	0.030
Energy consumption 8 m pumping head	kWh/m^3 treated	0.035	0.035
Energy consumption backwash water	kWh/m^3 treated	0.002	0.020

Technology design for 100,000 PE WWTP at 150 g COD			
Parameter	**Unit**	**Value**	**Value – incl. N and P**
Technology design			
Selected variant for design elaboration	-	03-STEP without nutrient removal	03-STEP with nutrient removal
Design flow (technology)	m^3/h	1,040	1,040
Annual volume to be treated with the technology	m^3/year	5,365,500	5,365,500
Share of annual effluent treated	%	70	70
Oxidation with ozone and/or H_2O_2			
O_3 dosage per gram DOC	g O_3/g DOC	0.4	0.4
O_3 dosage - nominal (at 11 mg DOC/l)	g O_3/h	2,695	2,695
O_3 dosage - maximum	g O_3/h	4,576	4,576
O_3 reactor volume	m^3	173	173
O_3 reactor depth	m	5	5
Number of O_3 reactors		2	2
O_3 production from		oxygen	oxygen
O_2 consumption for O_3 production	ton/y	236	236
H_2O_2 dosing	kg H_2O_2/m^3	No	No
Granular activated carbon (GAC)			
Oxygen dosing	g O_2/h	n.a.	n.a.
Hydraulic loading	m/h	10 to 15	10 to 15
Required bed volume	m^3	295	295
Bed depth	m	2,2	2,2
Filter surface area	m^2	134	134

Configuration (upflow/downflow)	-	Downflow	Downflow
Number of filters		4	4
GAC type	-	GAC 612 WFD	GAC 612 WFD
GAC granule size (diameter)	mm	1.7-3.35	1.7-3.35
Activated carbon granule density	kg/m^3	350-550	350-550
Metal salt dosage	kg Fe^{3+}/d	0	140-200
Methanol dosage (99.8%)	kg/d	0	225
Additional sludge removal	ton DS/y	0	64
Backwash water			
Backwash flow	m^3/h	6	60
Backwash time fraction	%	1	10
Frequency for all filters combined	number of times/h	0.019	0.188
Duration	min	0	15
Staffing			
Full time equivalents (FTE)	FTE/y	1	1
Energy consumption			
Total energy consumption for technology, incl. pumping and backwash	kWh/y	617,524	714,103
Minimum pumping head for technology	m	5	5
Energy consumption per component - ozonation	kWh/y	258,000	258,000
Energy consumption per component - 1-STEP	kWh/y	161,000	161,000
Energy consumption 8 m pumping head	kWh/y	187,793	187,793
Energy consumption backwash	kWh/y	10,731	107,310

Results based on IPMV criteria for 100,000 PE WWTP at 150 g COD			
		Updated without N and P removal	**Updated with N and P removal**
Parameter	**Unit**	**value 2024**	**value 2024**
Removal efficiency micropollutants			
In substream (7/11 NL indicator substances)	%	Up to 95%	Up to 95%
In substream (11 NL indicator substances)	%	80	80
In full WWTP + post-treatment (7/11 NL indicator substances)	%	80	80
In substream (EU substances)	%	>80	>80
In full WWTP + post-treatment (EU substances)	%	80	80
CO_2 footprint			
CO_2 footprint	g CO_2/m^3 treated	179	306
CO_2 footprint	g CO_2/m^3 total WWTP	125	214
Costs (incl. VAT)			
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 treated	0.24-0.37	not updated in 2024
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 total WWTP	0.17-0.26	not updated in 2024
Ecotoxicity			
Ecotoxicity reduction	%	>50	>50

Co-benefits		**Updated without N and P removal**	**Updated with N and P removal**
Parameter	**Unit**	**value 2024**	**value 2024**
Additional total N removal	%	negligible	>70%
Additional ammonium removal	%	negligible	10-20%
Additional total P removal	%	neutral, possible via DS capture or with additional metal salt dosing	50-80%

Total P concentration at technology inlet	mg P/l		
Bromide concentration at technology inlet	mg bromide/l	300-700	300-700
Bromate concentration at technology outlet	mg bromate/l	below detection limit	below detection limit
Additional PFAS removal in technology	%	see STOWA 2024-29	see STOWA 2024-29
Additional disinfection in technology (*E. coli* removal)	reduction factor (log)	not measured	not measured
Additional antibiotic resistant bacteria removal in technology	%	see STOWA 2024-30	see STOWA 2024-30

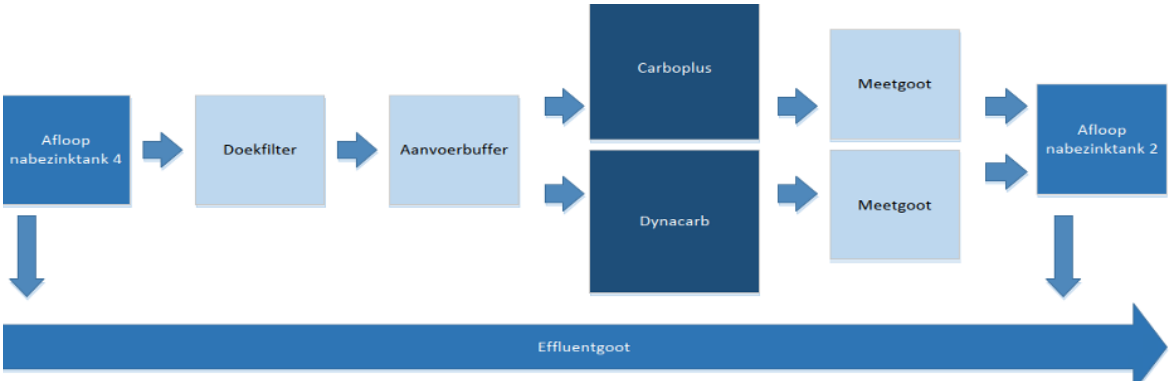
Technology readiness level (TRL)			
Parameter	**Unit**	**Value**	
TRL		8	
		A demonstration-scale installation is already running	
Outstanding questions (scale-up)		Extensive monitoring and optimisation of the full-scale application could result in further extension of the service life. This would lead to lower operating costs and a smaller CO_2 footprint, as well as better understanding of bromate formation and removal in O3-STEP and advanced nutrient removal.	
Outstanding questions (optimisation)			
Outstanding questions (operation / new pilot studies)			

TECHNOLOGY NAME: CONTINUOUS UPFLOW µGAC

Technology description

Unlike the conventional GAC filter, the upflow GAC filter is fed from the bottom and flows upward. This upward flow keeps the activated carbon in motion, resulting in better contact between the activated carbon and water and avoiding short-circuiting. The technology can achieve good removal efficiencies with a smaller CO_2 footprint, particularly when reactivated carbon is used. Two GAC upflow filters were evaluated: CarboPlus and DynaCarbon.
CarboPlus is a fluidised-bed activated carbon filter. Depending on the volume of (waste)water treated, fresh carbon is added and saturated carbon is removed several times per week. This enables the filter to be continually operated.
DynaCarbon is a moving-bed reactor in which activated carbon is added once and then continually washed using a mammoth pump.
Both pilots were implemented with reactivated carbon. The expected advantage compared to the GAC reference is reduced carbon consumption.

Process integration schematic (block diagram)



Pilot installation as implemented within the IPMV			
Parameter	**Unit**	**CarboPlus**	**DynaCarbon**
WWTP location	-	(Hapert)	(Hapert)
Period	month/year – month/year	February 2021 – November 2021	February 2021 – November 2021
Pilot pretreatment		Sobye cloth filter	Sobye cloth filter
Pilot installation capacity	m^3/h	0,25	5
Tested variations	e.g., dosage in mg PAC/l or g O_3/g DOC	15, 18, 20, 30 mg GAC/l	5.9 – 7.7 m/u
Continuous/batch testing	-	Continuous	Continuous
Some specific information: e.g., PAC type, O_3 production from air/O_2, bromide concentrations, DOC		Cyclecarb 305, Chemviron	Cyclecarb 401, Chemviron
Analyses conducted		indicator substances, macro-parameters, PFAS and ecotoxicity	indicator substances, macro-parameters, PFAS and ecotoxicity

Design assumptions for full-scale installation			
Parameter	**Unit**	**CarboPlus**	**DynaCarbon**
Granular activated carbon (GAC)			
Oxygen dosage	mg O_2/l	n.a.	n.a.
Hydraulic loading	m/h	,	5.9 - 7.7
EBCT at DWF design peak	min	7 min	18 min
EBCT at average flow	min	10 min	28
Required bed volume	m^3	0.028	1.6
Bed depth	m	1.05	3
Filtration rate at DWF design peak	m/h	15	7
Filtration rate, at average flow	m/h		
Configuration (upflow/downflow)	-	Upflow	Upflow
GAC type	-	Cyclecarb 305, Chemviron	Cyclecarb 401, Chemviron
GAC granule size (diameter)	mm	0.5 mm	2 mm

Carbon service life	Months	n.a.	11
Carbon service life	bed volumes	n.a.	15,000 – 25,000
Share of regenerated and non-fossil carbon	% regenerated of total	80	80
Carbon dosage	g/m³	20	n.a.
Activated carbon granule density	kg/m³	450	450
Additional sludge to be removed	kg DS/m³ treated	0	0
Prefiltration			
Filter type	-	Sobye cloth filter	Sobye cloth filter
Pore size	µm	500 µm	500 µm
Backwash water			
Backwash water type	-	e.g., effluent	e.g., effluent
Backwash flow	% of incoming flow	0.2	5
Energy consumption			
Total energy consumption for technology, incl. pumping and backwash	kWh/m³ treated	0.048	0.108
Minimum pumping head for technology	m	4	6.8
Energy consumption for post-treatment	kWh/m³ treated	0.003	0.020
Energy consumption, CarboPlus: 8 m pumping head and DynaCarbon: 17.8 m pumping head	kWh/m³ treated	0.035	0.078
Energy consumption recirculation pumps	kWh/m³ treated	0.009	0.000
Energy consumption backwash, Carboplus: 0.2% and DynaCarbon: 5%	kWh/m³ treated	0.000	0.010

Technology design for 100,000 PE WWTP at 150 g COD			
Parameter	**Unit**	**CarboPlus**	**DynaCarbon**
Technology design			
Selected variant for design elaboration	-	n.a.	n.a.
Design flow (technology)	m³/h	1040	1040
Annual volume to be treated with the technology	m³/year	6,132,000	6,132,000
Share of annual effluent treated	%	80	80
Granular activated carbon (GAC)			
Oxygen dosing	g O_2/h	n.a.	n.a.
Hydraulic loading	m/h	13	6.3
Required bed volume	m³	122	495
Bed depth	m	3	3
Filter surface area	m²	81	165
Configuration (upflow/downflow)	-	Upflow	Upflow
Number of filters		4	3
GAC granule size (diameter)	mm		
Carbon dosage	kg/d	504	504
Activated carbon granule density	kg/m³	450	450
Additional sludge removal	ton DS/y	0	0
Backwash water			
Backwash flow	m³/h	1	35
Staffing			
Full time equivalents (FTE)	FTE/y	0.5	0.5
Energy consumption			
Total energy consumption for technology, incl. pumping and backwash	kWh/y	295,317	663,879
Minimum pumping head for technology	m	4	6, 8
Energy consumption for post-treatment	kWh/y	21,189	125,029
Energy consumption pumping, CarboPlus: 8 m and DynaCarbon: 17.8 m pumping head	kWh/y	214,620	477,530

Energy consumption recirculation pumps	kWh/y	57,055	0
Energy consumption backwash, Carboplus: 0.2% and DynaCarbon: 5%	kWh/y	2,453	61,320

Results based on IPMV criteria for 100,000 PE WWTP at 150 g COD			
		CarboPlus updated	**DynaCarbon updated**
Parameter	**Unit**	**value 2024**	**value 2024**
Removal efficiency micropollutants			
In substream (7/11 NL indicator substances)	%	80 - 90	80 - 90
In substream (11 NL indicator substances)	%	77	
In full WWTP + post-treatment (7/11 NL indicator substances)	%	80 - 85	80 - 85
In substream (EU substances)	%	70 - 90	70 - 90
In full WWTP + post-treatment (EU substances)	%	75 - 85	75 - 85
CO_2 footprint			
CO_2 footprint	g CO_2/m^3 treated	201	234
CO_2 footprint	g CO_2/m^3 total WWTP	161	187
Costs (incl. VAT)			
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 treated	0.17-0.26	0.25-0.37
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 total WWTP	0.14-0.21	0.20-0.29
Ecotoxicity			
Ecotoxicity reduction	%		

Co-benefits		**Updated**	**Updated**
Parameter	**Unit**	**value 2024**	**value 2024**
Additional total N removal	%	neutral	neutral
Additional ammonium removal	%	neutral	neutral
Additional total P removal	%	neutral	neutral
Additional PFAS removal in technology	%	see STOWA 2024-29	see STOWA 2024-29
Additional disinfection in technology (*E. coli* removal)	reduction factor (log)	neutral	neutral
Additional antibiotic resistant bacteria removal in technology	%	see STOWA 2024-30	see STOWA 2024-30

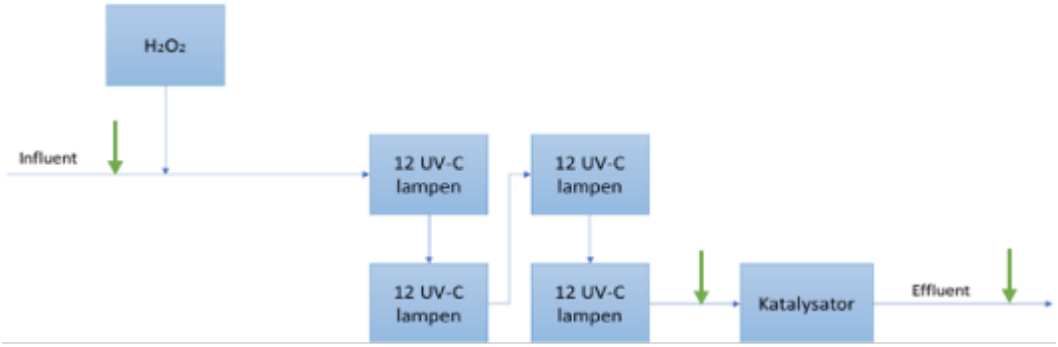
Technology readiness level (TRL)			
Parameter	**Unit**	**Value**	**Value**
TRL		8	8
		A number of uncertainties remain to be investigated	A number of uncertainties remain to be investigated
Outstanding questions (scale-up)		For the CarboPlus installation, further research is needed on backwash water use, operation of automatic carbon dosing and performance at other WWTP sites.	For Dynacarbon, further research is needed on pretreatment requirements, residence time and GAC service life.
Outstanding questions (optimisation)			
Outstanding questions (operation / new pilot studies)			

TECHNOLOGY NAME: ULTRAVIOLET LIGHT WITH HYDROGEN PEROXIDE (UV + H_2O_2)

Technology description

In the oxidative UV/H_2O_2 process, hydrogen peroxide (H_2O_2) is first dosed (in excess), after which the water is irradiated with UV light (254 nm). To break down the remaining H_2O_2, the water is passed through a catalyst bed, where H_2O_2 is catalytically converted into H_2O and O_2. After the catalyst bed, the treated water is discharged downstream into the effluent channel of the WWTP. The irradiation of H_2O_2 produces hydroxyl radicals. The process combines three reaction mechanisms: (1) photolysis, (2) oxidation by hydroxyl radicals and (3) oxidation by H_2O_2. Some pharmaceutical residues are primarily degraded by photolysis, while others are hardly affected by photolysis and mainly broken down through oxidation. Expected advantages compared to the reference technology are increased removal efficiency and a better SIMONI score (a measurement of ecotoxicity).
During the pilot study, the transmission was low at 40%, meaning the removal efficiency did not meet the 80% target for the IPMV evaluation. Pretreatment can increase UV transmission. Therefore, the fact sheet and evaluation report are based on the results from the, albeit more indicative, follow-up study using sand filtration.

Process integration schematic (block diagram)



Pilot installation:
The schematic shows the pilot installation. For full-scale application, prefiltration is needed to improve UV transmittance (e.g., sand filtration with polyaluminium chloride (PAlCl) dosing).

Pilot installation as implemented within the IPMV

Parameter	Unit	Value
WWTP location	-	Aarle Rixtel
Period	month/year – month/year	September 2018 – June 2019
Pilot pretreatment		
Pilot installation capacity	m^3/h	15 (2 reactors, each with 12 lamps)
Tested variations		UV dose is dependent on UV transmittance (UVT). Tested with 30 ppm H_2O_2 and resulting UV doses ranging from 17,000 J/m^2 (at 40% UVT) to 11,000 J/m^2 (at 60% UVT)
Continuous/batch testing	-	Continuous
Some specific information: e.g., PAC type, O_3 production from air/O_2, bromide concentrations, DOC		UV transmittance of Aarle-Rixtel effluent was relatively low (40%), meaning that either a high UV dose was required or improvement of transmittance via prefiltration (e.g., by sand filtration, as in this pilot, or by nanofiltration combined with UV/H_2O_2, as tested by another IPMV project)
Analyses conducted		macro-parameters, Aquon pharmaceuticals package, pesticides, industrial chemicals, personal care products, bromide, bromate, hydrogen peroxide, glymes, *E. coli*, enterococci, etc.

Design assumptions for full-scale installation		
Parameter	**Unit**	**Value**
UV technologies with H_2O_2 including pretreatment to increase UV transmittance to UVT = 60%		
Number of UV lamps	m^3 treated per UV lamp	9,581
Hydraulic retention time (HRT) UV reactor/tube	min	a few
UV lamp power	W/lamp	550
UV dosage	J/m^2	15000
Transmittance	%	60
H_2O_2 dosage	ppm	30
Sand filtration as pretreatment to improve UV transmittance		
Backwash water (expert opinion)	% of incoming flow	1
Sludge production (excluding sand filtration and PAlCl dosing)	kg DS/m^3 treated	0
Filter type	-	SF + polyaluminium chloride (PAlCl)
PAlCl dosage (range)	ppm	6-12
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/m^3 treated	0.95
Minimum pumping head for technology	m	4-8
Energy consumption UV lamps	kWh/m^3 treated	0.90
Energy consumption 8 m pumping head	kWh/m^3 treated	0.035
Energy consumption sand filter	kWh/m^3 treated	0.015
Backwash water 1% for sand filter	kWh/m^3 treated	0.002

Technology design for 100,000 PE WWTP at 150 g COD		
Parameter	**Unit**	**Value**
Technology design		
Selected variant for design elaboration	-	pretreatment with sand filter to improve transmittance from 40% to 60%
Design flow (technology)	m^3/h	1,040
Annual volume to be treated with the technology	m^3/year	6,132,000
Share of annual effluent treated	%	80
UV technologies with H_2O_2 including pretreatment to increase UV transmittance to UVT = 60%		
Number of UV reactors	Number	20
Number of UV lamps (48 lamps/reactor, estimated at UVT=60%)	Number	960
Total UV lamp power	kW	528
UV dosage	J/m^2	15,000
Transmittance	%	60
H_2O_2 dosage (100% H_2O_2)	kg/year	183,960
Citric acid rinse for cleaning UV lamps	g/m^3	1.24
Sand filter		
Sludge production (excluding sand filtration and PAlCl dosing)	ton DS/y	0
Prefiltration		
Filter type	-	SF + polyaluminum chloride (PAlCl)
AlCl dosage at 12 ppm as Al	kg AlCl/y	363,832
Staffing		
Full time equivalents (FTE)	FTE/y	1
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/y	5,837,664
Minimum pumping head for technology	m	8
Energy consumption UV lamps	kWh/y	5,518,800
Energy consumption 8 m pumping head	kWh/y	214,620

Energy consumption sand filter	kWh/y	91,980
Backwash water 1% for sand filter	kWh/y	12,264

Results based on IPMV criteria for 100,000 PE WWTP at 150 g COD		
		Updated
Parameter	**Unit**	**value 2024**
Removal efficiency micropollutants		
In substream (7/11 NL indicator substances)	%	>90
In substream (11 NL indicator substances)	%	approx. 90
In full WWTP + post-treatment (7/11 NL indicator substances)	%	78
In substream (EU substances)	%	80-85
In full WWTP + post-treatment (EU substances)	%	approx. 75
CO_2 footprint*		
CO_2 footprint	g CO_2/m^3 treated	717
CO_2 footprint	g CO_2/m^3 total WWTP	574
Costs (incl. VAT)*		
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 treated	0.61-0.92
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 total WWTP	0.49-0.74
Ecotoxicity		
Ecotoxicity reduction	%	50-75

Co-benefits		**Updated**
Parameter	**Unit**	**value 2024**
Additional total N removal	%	neutral
Additional ammonium removal	%	neutral
Additional total P removal	%	neutral
Bromide concentration at technology inlet	mg bromide/l	0.5-1
Bromate concentration at technology outlet	µg bromate/l	<0.2
Additional PFAS removal in technology	%	see STOWA 2024-29
Additional disinfection in technology (*E. coli* removal)	reduction factor (log)	2-2.5
Additional antibiotic resistant bacteria removal in technology	%	see STOWA 2024-30

Technology readiness level (TRL)		
Parameter	**Unit**	**Value**
TRL		5 to 6
		Energy consumption is still high. Additional research is needed on ways to reduce energy demand.
Outstanding questions (improvements, scale-up, operation and new pilot studies)		Development of energy-efficient UV lamps, better understanding of causes of low UV transmittance in effluent. Research on potential for further reductions in energy consumption, such as with more effective pretreatment and by optimising reactor configuration, among others.

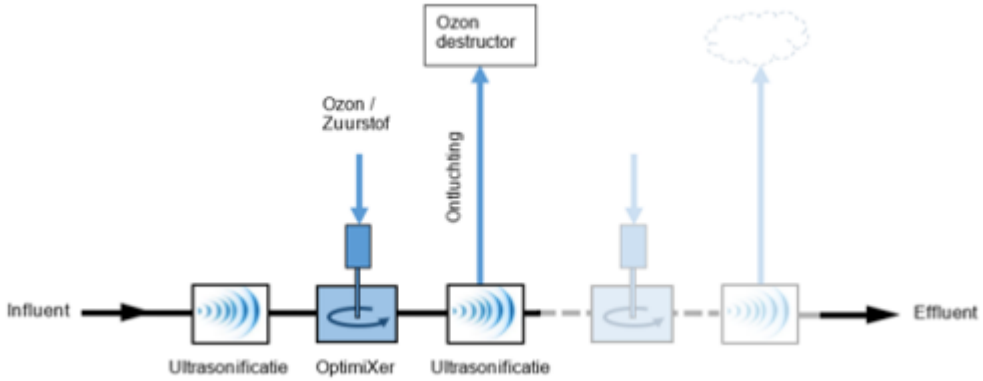
* Investment costs are based on the installation needed at 40% transmittance; i.e., with 50% more UV lamps than indicated in this factsheet and including a sand filter. The annual costs and CO_2 footprint do not include the extra sludge resulting from AlCl dosing on the sand filter.

TECHNOLOGY NAME: OZONATION AND ULTRASOUND

Technology description

In O_3 + ultrasound (USONiQ) a combination of ozone and ultrasonic sound is applied. Ultrasound enhances the ozonation process in several ways: it disrupts bacterial clusters; it breaks chemical bonds within cell membranes; it improves the formation of free radicals from ozone; and it promotes the transfer of ozone from the gas phase to the fluid phase. The system is made up of a stainless steel tube-shaped reactor. Along this pipe, ultrasound, ozonation and ultrasound again are applied in sequence: Ultrasound is applied first, followed by the addition of ozone close to a patented mixing disk that ensures optimal mixing of the dosed ozone. After that, ultrasound is applied again. Ultrasound generators are distributed along the pipe in the sections that serve as reaction chamber for ultrasound treatment. There are several advantages compared to the references: the USONiQ unit has a substantially smaller CO_2 footprint compared to a conventional ozonation installation; with USONiQ, shorter residence times and lower O_3 dosages suffice to achieve the same removal efficiencies as conventional treatment installations.

Process integration schematic (block diagram)



Pilot installation as implemented within the IPMV

Parameter	Unit	Value
WWTP location	-	Winterswijk
Period	day/month/year	13 and 14 April 2022
Pilot pretreatment		n.a.
Pilot installation capacity	m^3/h	1
Tested variations	g O_3/g DOC	0.16, 0.35, 0.55, 0.58 and 0.72
Continuous/batch testing	-	batch
Some specific information: e.g., PAC type, 03 production from air/02, bromide concentrations, DOC		Bromide spike of 1,000 µg/l
Analyses conducted		DOC, micropollutants, bromide, bromate

Design assumptions for full-scale installation

Parameter	Unit	Value
Oxidation with ozone and/or H_2O_2		
O_3 dosage - nominal	g O_3/g DOC	0.55
O_3 dosage - nominal (at 11 mg DOC/l)	g O_3/m^3	6.05
O_3 reactor contact time	min	a few minutes
O_3 reactor depth	m	n.a.
O_3 input		USONiQ system
H_2O_2	ppm	0
Sludge formed	kg DS/m^3 treated	0
Backwash water	% of incoming flow	0
Ultrasound		
Ultrasound power use	ratio ultrasound: O_3 generation	1 : 3-3.5
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/m^3 treated	0.13

Minimum pumping head for technology	m	0-2
Energy consumption per component	kWh demand ultrasound : O_3 generation	1 : 3-3.5
Energy consumption O_3 + ultrasound	kWh/m³ treated	0.097
Energy consumption 8 m pumping head	kWh/m³ treated	0.035

Technology design for 100,000 PE WWTP at 150 g COD		
Parameter	**Unit**	**Value**
Technology design		
Selected variant for design elaboration	-	n.a.
Design flow (technology)	m³/h	1,040
Annual volume to be treated with the technology	m³/year	5,365,500
Share of annual effluent treated	%	70
Oxidation with ozone and/or H_2O_2		
O_3 dosage per gram DOC	g O_3/g DOC	0.55
O_3 dosage - nominal (at 11 mg DOC/l)	kg O_3/h	4.4
O_3 dosage - maximum	kg O_3/h	6.3
O_3 reactor volume	m³	n.a.
O_3 reactor depth	m	tubular reactor
O_2 consumption for O_3 production	ton/y	325
H_2O_2 dosage	kg H_2O_2/m³	0
Ultrasound		
Ultrasound power use	kWh/d	355
Staffing		
Full time equivalents (FTE)	FTE/y	1
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/y	705,793
Minimum pumping head for technology	m	0-2
Energy consumption O_3 + ultrasound	kWh/y	518,000
Energy consumption 8 m pumping head	kWh/y	187,793

Results based on IPMV criteria for 100,000 PE WWTP at 150 g COD		
		Updated
Parameter	**Unit**	**value 2024**
Removal efficiency micropollutants		
In substream (7/11 NL indicator substances)	%	92
In substream (11 NL indicator substances)	%	86
In full WWTP + post-treatment (7/11 NL indicator substances)	%	85-90
In substream (EU substances)	%	85-90
In full WWTP + post-treatment (EU substances)	%	80-85
CO_2 footprint		
CO_2 footprint	g CO_2/m³ treated	106
CO_2 footprint	g CO_2/m³ total WWTP	74
Costs (incl. VAT)		
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m³ treated	0.10-0.015
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m³ total WWTP	0.07-0.11
Ecotoxicity		
Ecotoxicity reduction	%	not measured

Co-benefits		**Updated**
Parameter	**Unit**	**value 2024**
Additional total N removal	%	not measured
Additional ammonium removal	%	not measured
Additional total P removal	%	neutral
Bromide concentration at technology inlet	mg bromide/l	1 (spiked)
Bromate concentration at technology outlet	mg bromate/l	0.004
Bromate formation relative to bromide at inlet	%	0.4 (at high spike)
Additional PFAS removal in technology	%	not measured
Additional disinfection in technology (*E. coli* removal)	reduction factor (log)	not measured
Additional antibiotic resistant bacteria removal in technology	%	not measured

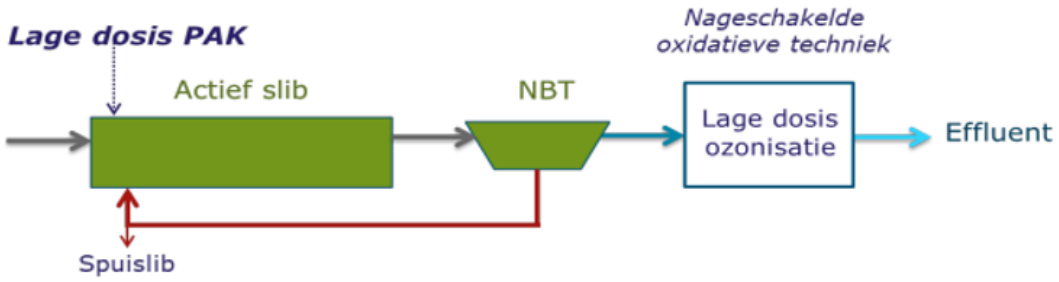
Technology readiness level (TRL)		
Parameter	**Unit**	**Value**
TRL		5
Outstanding questions (operation / new pilot studies)		Energy consumption, testing over a longer term with variable flow conditions

TECHNOLOGY NAME: PAC + O_3

Technology description

PAC + O_3 is a technology in which powdered activated carbon (PAC) is dosed into the activated sludge process and the effluent is subsequently treated with ozone. The concept applies a lower-dosage PACAS with a post-treatment ozonation step that also uses a relatively low specific ozone dose. By making use of two reaction mechanisms, adsorption and oxidation, both can be applied in a less intensive way than each they was used stand-alone. Expected advantages include a lower PAC dosage than conventional PACAS, reduced bromate formation and removal of a broader spectrum of substances.

Process integration schematic (block diagram)



Pilot installation as implemented within the IPMV		
Parameter	**Unit**	**Value**
WWTP location	-	Leiden-Noord
Period	month/year – month/year	July 2024 - October 2024
Pilot pretreatment		**n.a.**
Pilot installation capacity	m^3/h	5 (ozone)
Tested variations	e.g., dosage in mg PAC/l or g O_3/g DOC	PAC dosages of 5, 7.5, 10 and 12.5 mg/l and specific ozone dosages between 0.2 and 0.7 g O_3/g DOC were tested
Continuous/batch testing	-	batch
Some specific information: e.g., PAC type, 03 production from air/02, bromide concentrations, DOC	PAC type	Pulssorb WP235
Analyses conducted		micropollutants, ecotoxicity, bromate, N&P, PFAS, antibiotic resistance

Design assumptions for full-scale installation		
Parameter	**Unit**	**Value**
Oxidation with ozone and/or H_2O_2		
O_3 dosage - nominal	g O_3/g DOC	0.3 - 0.7
O_3 dosage - nominal (at 11 mg DOC/l)	g O_3/m^3	
O_3 reactor contact time	min	15
O_3 reactor depth	m	2 - 6.5
O_3 input		all systems possible
H_2O_2	ppm	0
PACAS		
PAC dosage - nominal	mg/l	7.5
PAC dosage - max	mg/l	12.5
Additional sludge to be removed	kg DS/m^3 treated	0.006
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/m^3 treated	0.145
Minimum pumping head for technology	m	1 - 6
Energy consumption PAC corresponding to 5,365,500 m^3/year	kWh/m^3 treated	0.025
Energy consumption ozonation	kWh/m^3 treated	0.085
Energy consumption 8 m pumping head	kWh/m^3 treated	0.035

Technology design for 100,000 PE WWTP at 150 g COD		
Parameter	**Unit**	**Value**
Technology design		
Selected variant for design elaboration	-	n.a.
Design flow (technology)	m^3/h	1,040
Annual volume to be treated with the technology	m^3/year	7,665,000 (PAC) 5,365,500 (ozonation)
Share of annual effluent treated	%	100 (PAC) and 70 (ozonation)
Oxidation with ozone and/or H_2O_2		
O_3 dosage per gram DOC	g O_3/g DOC	0.5
O_3 dosage - nominal (at 11 mg DOC/l)	kg O_3/h	3.4
O_3 dosage - maximum	kg O_3/h	5.7
O_3 reactor volume	m^3	260
O_3 reactor depth	m	6
O_3 production from		oxygen
O_2 consumption for O_3 production	ton/y	295
H_2O_2 dosage	kg H_2O_2/m^3	0
PACAS		
PAC dosage - nominal	kg/d	126
PAC dosage - max		The PAC dosage is proportional to the flow up to a maximum of 2x DWF = 80% of annual volume
Sludge production	ton ds/y	46
Staffing		
Full time equivalents (FTE)	FTE/y	1
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/y	780,517
Minimum pumping head for technology	m	6
Energy consumption PAC	kWh/y	136,656
Energy consumption ozonation	kWh/y	456,068
Energy consumption 8 m pumping head	kWh/y	187,793

Results based on IPMV criteria for 100,000 PE WWTP at 150 g COD		
		Updated
Parameter	**Unit**	**value 2024**
Removal efficiency micropollutants		
In substream (7/11 NL indicator substances)	%	90-95
In substream (11 NL indicator substances)	%	85-90
In full WWTP + post-treatment (7/11 NL indicator substances)	%	85
In substream (EU substances)	%	85-90
In full WWTP + post-treatment (EU substances)	%	80
CO_2 footprint		
CO_2 footprint	g CO_2/m^3 treated	206
CO_2 footprint	g CO_2/m^3 total WWTP	144
Costs (incl. VAT)		
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 treated	0.20-0.31
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 total WWTP	0.14-0.21
Ecotoxicity		
Ecotoxicity reduction	%	65-68

Co-benefits		**Updated**
Parameter	**Unit**	**value 2024**
Additional total N removal	%	neutral
Additional ammonium removal	%	neutral
Additional total P removal	%	neutral
Bromide concentration at technology inlet	mg bromide/l	0.32
Bromate concentration at technology outlet	mg bromate/l	0.004
Bromate formation relative to influent bromide	%	1.1%
Additional PFAS removal in technology	%	see STOWA 2024-29
Additional disinfection in technology (*E. coli* removal)	reduction factor (log)	not measured
Additional antibiotic resistant bacteria removal in technology	%	see STOWA 2024-30

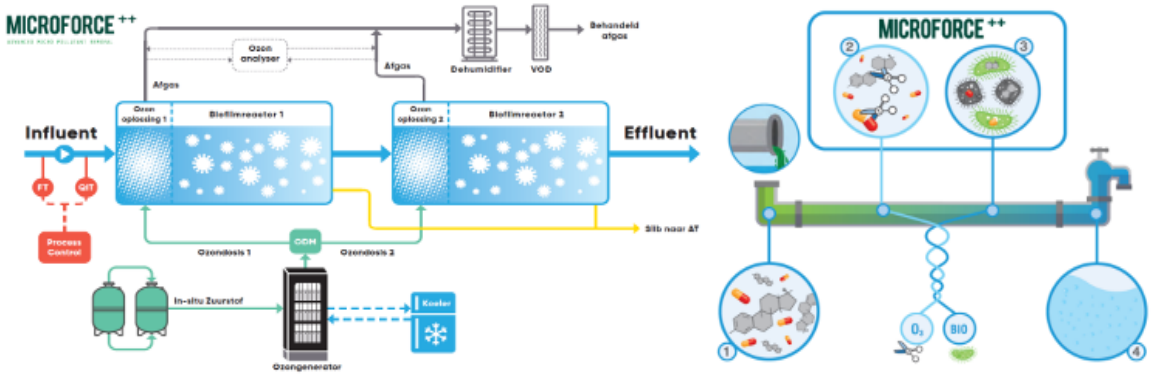
Technology readiness level (TRL)		
Parameter	**Unit**	**Value**
TRL		7-8
		The separate technologies already proven at full scale
Outstanding questions (scale-up)		Optimum combination of PAC and ozone dosing to meet EU target (80%), mitigation of bromate formation, cost and sustainability optimisation
Outstanding questions (optimisation)		n.a.
Outstanding questions (operation / new pilot studies)		n.a.

TECHNOLOGY NAME: MICROFORCE

Technology description

MicroForce++ combines ozonation and biological oxidation. The MicroForce++ process consists of two consecutive, in-series arranged O_3/ bioreactors, each operated with a specific ozone dose. In each reactor, the effluent is first treated with ozone in the ozonation compartment, followed by a biological reactor using a biofilm carrier technology for further degradation. The expected advantage of the technology is that introducing a biological step reduces the ozone demand compared to conventional practice.

Process integration schematic (block diagram)



Pilot installation as implemented within the IPMV

Parameter	Unit	Value
WWTP location	-	Walcheren
Period	month/year – month/year	42 weeks
Pilot pretreatment		No pretreatment required
Pilot installation capacity	m^3/h	4 to 16
Tested variations		O_3 between 0.15 and 0.5 g O_3/g DOC and hydraulic retention time (HRT) between 3.75 and 15 min per reactor
Continuous/batch testing	-	Continuous
Some specific information: e.g., PAC type, O_3 production from air/O_2, bromide concentrations, DOC		Tested with O_2 from air, but compatible with liquid oxygen
Analyses conducted		

Design assumptions for full-scale installation

Parameter	Unit	Value
Oxidation with ozone and/or H_2O_2		
O_3 dosage - nominal	g O_3/g DOC	between 0.25 and 0.43
O_3 dosage - nominal (at 11 mg DOC/l)	g O_3/m^3	
O_3 reactor contact time	min	15
O_3 reactor depth	m	2
O_3 input		PureBlue system
H_2O_2	ppm	0
Biological reactor in combination with O_3		
Carrier type	-	HDPE rings Ø 17 mm, 5 mm thickness, specific surface 1,150 m^2/m^3
Carrier service life	Months	
Carrier density	kg/m^3	
Biological reactor contact time	min	between 7.5 and 15
Biological reactor height	m	2
EBCT minimum	min	3.75
EBCT nominal	min	15

Oxygen setpoint ramp-up	mg/l	
Sludge formed	kg DS/m^3 treated	0.003
Backwash water	% of incoming flow	1
Metal salt dosage	mg Fe^{3+}/L	0
Metal salt dosage	mol Fe/mol P to be removed	0
Carbon source dosage (specify type)	mg/l	0
Prefiltration		
Filter type	-	n.a.
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/m^3 treated	0.105
Minimum pumping head for technology	m	2.5
Energy consumption pumps and miscellaneous	kWh/m^3 treated	0.007
Energy consumption ozonation	kWh/m^3 treated	0.061
* Energy consumption ozone input	kWh/m^3 treated	0.014
* Energy consumption O_2 to O_3	kWh/m^3 treated	0.047
Energy consumption 8 m pumping head	kWh/m^3 treated	0.035
Energy consumption backwash water (1%)	kWh/m^3 treated	0.002

Technology design for 100,000 PE WWTP at 150 g COD		
Parameter	**Unit**	**Value**
Technology design		
Selected variant for design elaboration	-	n.a.
Design flow (technology)	m^3/h	1,047
Annual volume to be treated with the technology	m^3/year	6,130,000
Share of annual effluent treated	%	80
Oxidation with ozone and/or H_2O_2		
O_3 dosage per gram DOC	g O_3/g DOC	0.43
O_3 dosage - nominal (at 11 mg DOC/l)	kg O_3/h	3.3
O_3 dosage - maximum	g O_3/h	5.0
O_3 reactor volume	m^3	262
O_3 reactor depth	m	2
O_3 production from		oxygen
O_2 consumption for O_3 production	ton/y	290
H_2O_2 dosage	kg H_2O_2/m^3	0
Biological reactor in combination with O_3		
Biological reactor height	m	2
Carrier type		HDPE rings Ø 17 mm, 5 mm thick, specific surface 1,150 m^2/m^3
Carrier volume	m^3	70
Contact time	min	15
Metal salt dosage	kg Fe^{3+}/d	0
Additional sludge removal	ton DS/y	18
Prefiltration		
Filter type	-	n.a.
Staffing		
Full time equivalents (FTE)	FTE/y	1
Energy consumption		**MicroForce + liquid oxygen**
Total energy consumption for technology, incl. pumping and backwash	kWh/y	643.650
Minimum pumping head for technology	m	3
Energy consumption pumps and miscellaneous	kWh/y	42,910
Energy consumption ozonation	kWh/y	373,930

* Energy consumption ozone input	kWh/y	85,820
* Energy consumption O_2 to O_3	kWh/y	288,110
Energy consumption 8 m pumping head	kWh/y	214,550
Energy consumption backwash water (1%)	kWh/y	12,260

Results based on IPMV criteria for 100,000 PE WWTP at 150 g COD		
		Updated
Parameter	**Unit**	**value 2024**
Removal efficiency micropollutants		
In substream (7/11 NL indicator substances)	%	approx. 85
In substream (11 NL indicator substances)	%	approx. 75
In full WWTP + post-treatment (7/11 NL indicator substances)	%	approx. 80
In substream (EU substances)	%	approx. 80
In full WWTP + post-treatment (EU substances)	%	75-80
CO_2 footprint		
CO_2 footprint	g CO_2/m^3 treated	86
CO_2 footprint	g CO_2/m^3 total WWTP	69
Costs (incl. VAT)		
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 treated	0.21-0.32
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 total WWTP	0.17-0.26
Ecotoxicity		
Ecotoxicity reduction	%	67

Co-benefits		Updated
Parameter	Unit	value 2024
Additional total N removal	%	NH4 and possibly NO_2
Additional ammonium removal	%	80
Additional total P removal	%	neutral
Bromide concentration at technology inlet	mg bromide/l	1.5-2
Bromate concentration at technology outlet	mg bromate/l	0.000
Additional PFAS removal in technology	%	see STOWA 2024-29
Additional disinfection in technology (*E. coli* removal)	reduction factor (log)	not measured
Additional antibiotic resistant bacteria removal in technology	%	see STOWA 2024-30

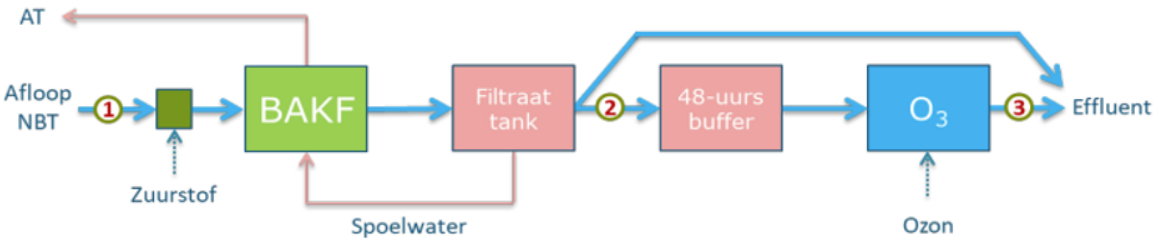
Technology readiness level (TRL)		
Parameter	**Unit**	**Value**
TRL		6
Outstanding questions (scale-up)		Service life of carrier material, nitrogen removal
Outstanding questions (optimisation)		
Outstanding questions (operation / new pilot studies)		

TECHNOLOGY NAME: AUREA (FORMERLY BO_3)

Technology description

The BO_3 technology is a two-step process consisting of biological activated carbon filtration (BACF) followed by ozonation for advanced removal of micropollutants and ecotoxicity reduction. In the first step, the BACF, organic components are biologically (partially) degraded in an aerobic environment. This includes the (partial) degradation of both DOC and a selection of pharmaceutical residues. The expected advantage of this technology is that, due to the preliminary degradation, a low ozone dose is sufficient to oxidise bio-recalcitrant components in the second step.

Process integration schematic (block diagram)



Pilot installation as implemented within the IPMV

Parameter	Unit	Value
WWTP location	-	Horstermeer
Period	month/year – month/year	October 2022 - April 2023
Pilot pretreatment		None (no prefilter)
Pilot installation capacity	m^3/h	0,8 - 2,2
Tested variant	e.g., dosage in mg PAC/l or g O_3/g DOC	0.1 – 0.4 g O_3/g DOC
Continuous/batch testing	-	BACF: continuous testing O_3: periodic continuous tests
Some specific information: e.g., PAC type, O_3 production from air/O_2, bromide concentrations, DOC		GAC type Norit 830P, O_3 from O_2, avg. DOC ~11 mg/l, bromide max. 0.68 mg/l
Analyses conducted		micropollutants, UV, DOC, N/P, biological effects

Design assumptions for full-scale installation

Parameter	Unit	Value
Oxidation with ozone and/or H_2O_2		
O_3 dosage - nominal	g O_3/g DOC	0.2 - 0.3
O_3 dosage - nominal (at 11 mg DOC/l)	g O_3/m^3	1.9 - 2.7
O_3 reactor contact time	min	7.5 - 9
O_3 reactor depth	m	2 - 6.5
O_3 input		all systems possible
Biological reactor in combination with O_3		
Carrier type	-	GAC
Carrier service life	months	180 - 240
Carrier density	kg/m^3	400 - 500
Biological reactor contact time	min	20 - 35
Biological reactor height	m	2 - 3.5
EBCT minimum	min	20
EBCT nominal	min	30
Oxygen setpoint ramp-up	mg/l	10 - 20
Sludge formed	kg DS/m^3 treated	0.003
Backwash water	% of incoming flow	0.5 - 1.0
Metal salt dosage	mg Fe^{3+}/L	0
Metal salt dosage	mol Fe/mol P to be removed	0
Carbon source dosage (specify type)	mg/l	0

Prefiltration		
Filter type	-	n.a.
Backwash water		
Backwash water type	-	e.g., effluent
Backwash water flow	% of incoming flow	1
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/m^3 treated	0.084
Minimum pumping head for technology	m	3 - 10
Energy consumption ozonation step:	kWh/m^3 treated	0.046
* Mixing etc. (20 W/m^3 treated)	kWh/m^3 treated	0.020
* O_3 production 10 kWh/kg O_3 * h	kWh/m^3 treated	0.026
Energy consumption BACF (based on GAC reference = <1W/m^3 treated)	kWh/m^3 treated	0.001
Energy consumption 8 m pumping head	kWh/m^3 treated	0.035
Energy consumption backwash water (1%)	kWh/m^3 treated	0.002

Technology design for 100,000 PE WWTP at 150 g COD		
Parameter	**Unit**	**Value**
Technology design		
Selected variant for design elaboration	-	Design 2 from STOWA 2023-48
Design flow (technology)	m^3/h	1,040
Annual volume to be treated with the technology	m^3/year	5,365,500
Share of annual effluent treated	%	70
Oxidation with ozone and/or H_2O_2		
O_3 dosage per gram DOC	g O_3/g DOC	0.3
O_3 dosage nominal (at 11 mg DOC/l-15% removal in BACF)	kg O_3/h	1.6
O_3 dosage - maximum	g O_3/h	2.7
O_3 reactor volume	m^3	130
O_3 reactor depth	m	2 - 6.5
Number of O_3 reactors		t.b.d.
O_3 production from		oxygen
O_2 consumption for O_3 production	ton/y	142
H_2O_2 dosage	kg H_2O_2/m^3	0
Granular activated carbon (GAC)		
Oxygen dosage	g O_2/h	3120
Hydraulic loading	m/h	5.6
Required bed volume	m^3	520
Bed depth	m	2.8
Filter surface area	m^2	186
Configuration (upflow/downflow)	-	Downflow
Number of filters		t.b.d.
Total filter surface area	m^2	186
GAC type	-	t.b.d.
GAC granule size (diameter)	mm	t.b.d.
Carbon dosage	kg/d	none
Activated carbon granule density	kg/m^3	450
Metal salt dosage	kg Fe^{3+}/d	0
Methanol dosage	kg/d	0
Additional sludge removal	ton DS/y	16
Backwash water		
Backwash water flow	% of incoming flow	1
Staffing		
Full time equivalents (FTE)	FTE/y	1

Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/y	451,863
Minimum pumping head for technology	m	3 - 10
Energy consumption ozonation step:	kWh/y	248,959
* Mixing etc. (20 W/m3 treated*)	kWh/y	107,310
* O_3 production (10 kWh/kg O_3 * h)	kWh/y	141,649
Energy consumption BACF (based on GAC reference = <1W/m^3 treated)	kWh/y	4,380
Energy consumption 8 m pumping head	kWh/y	187,793
Energy consumption backwash water (1%)	kWh/y	10,731

Results based on IPMV criteria for 100,000 PE WWTP at 150 g COD		
		Updated
Parameter	**Unit**	**value 2024**
Removal efficiency micropollutants		
In substream (7/11 NL indicator substances)	%	90
In substream (11 NL indicator substances)	%	75 - 80%
In full WWTP + post-treatment (7/11 NL indicator substances)	%	85
In substream (EU substances)	%	84
In full WWTP + post-treatment (EU substances)	%	77-80%
CO_2 footprint		
CO_2 footprint	g CO_2/m^3 treated	95
CO_2 footprint	g CO_2/m^3 total WWTP	66
Costs (incl. VAT)		
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 treated	0.18-0.27
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 total WWTP	0.13-0.19
Ecotoxicity		
Ecotoxicity reduction	%	50

Co-benefits		**Updated**
Parameter	**Unit**	**value 2024**
Additional total N removal	%	NH_4 and NO_2
Additional ammonium removal	%	99%
Ammonium concentration at technology inlet	mg N/l	~1
Ammonium concentration at technology outlet	mg N/l	<0,015
Additional total P removal	%	neutral, possibly via DS capture
Bromide concentration at technology inlet	mg bromide/l	170 - 680
Bromate concentration at technology outlet	mg bromate/l	<0.1 - 0.5
Bromate formation relative to bromide at inlet	%	<0.1%
Additional PFAS removal in technology	%	see STOWA 2024-29
Additional disinfection in technology (*E. coli* removal)	reduction factor (log)	not measured
Additional antibiotic resistant bacteria removal in technology	%	see STOWA 2024-30

Technology readiness level (TRL)		
Parameter	Unit	Value
TRL		6
		The separate technologies are already proven at full scale
Outstanding questions (scale-up)		GAC service life, need for/effect of potential pretreatment, optimum O_3 dosage, % backwash water

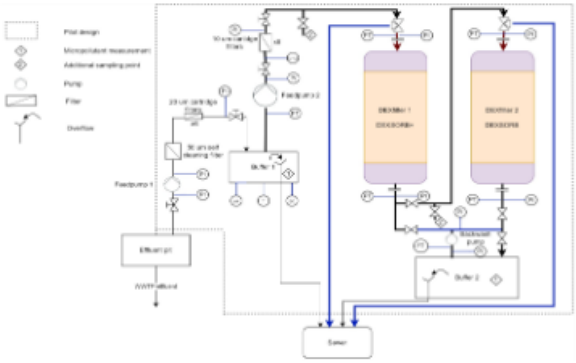
* Lower energy consumption compared to ozonation reference (30 W/m^3 treated), due to lower specific O_3 dosage for Aurea (BO_3)

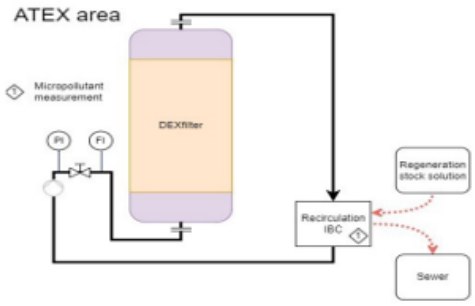
TECHNOLOGY NAME: DEX FILTER

Technology description

DEXSORB is the trade name for cyclodextrins produced by CycloPure for use in water treatment. The material originates from the air freshener industry. Cyclodextrins consist of cup-shaped molecules with a positive or negative charge, to which micropollutants can adsorb via a combination of electrostatic interactions, hydrophobic interactions and an exclusion mechanism based on molecule size. Expected advantages of this technology are more efficient removal of micropollutants with a more sustainable method of regeneration compared to the activated carbon reference.

Process integration schematic (block diagram)





Pilot installation as implemented within the IPMV

Parameter	Unit	Value
WWTP location	-	Lelystad
Period	month/year – month/year	February 2023 - August 2023
Pilot pretreatment		Self-cleaning filter and cartridge filter
Pilot installation capacity	m^3/h	0.5
Variations tested	e.g., dosage in mg PAC/l or g O_3/g DOC	none
Continuous/batch testing	-	Continuous
Some specific information: e.g., PAC type, O_3 production from air/O_2, bromide concentrations, DOC		Micropollutants, PFAS, ecotoxicity
Analyses conducted		

Design assumptions for full-scale installation

Parameter	Unit	Value
Alternative adsorption media		
Adsorption step		
Type of adsorption material		cyclodextrins
EBCT at DWF design peak	min	12.8
EBCT at average flow	min	10
Filtration rate	m/h	11
Surface area per filter column	m^2	0.000
Service life	months	4
Service life	bed volumes	4,000
Maximum filter diameter	m	0.24
Filter/zeolite bed height	m	1.55
Maximum bed expansion during backwash	%	40%
Expanded filter bed height	m	2.2
Adsorbent material weight	kg/m^3	399
Adsorbent material grain diameter	mm	0.2 - 1.0
Sludge production	kg DS/m^3 treated	0.005
Backwash water		
Backwash water type	-	filtered effluent
Backwash water flow	% of incoming flow	1.00

Backwash time fraction	%	1.00
Frequency for all filters combined	number of times/h	0.006
Duration	min	15
Effluent storage time in buffer tank for backwash	h	2
Regeneration		
Ethanol concentration	mg/l	67% ethanol, 5 cycles of 3 hours
Total regeneration duration	h	15
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/m³ treated	0.033
Minimum pumping head for technology	m	~ 2
Energy consumption DEX filter based on GAC	kWh/m³ treated	0.001
Energy consumption 8 m pumping head	kWh/m³ treated	0.031
Energy consumption backwash water (1%)	kWh/m³ treated	0.002

Technology design for 100,000 PE WWTP at 150 g COD		
Parameter	**Unit**	**Value**
Technology design		
Selected variant for design elaboration	-	DEXSORB (Variant 2)
Design flow (technology)	m³/h	1,040
Annual volume to be treated with the technology	m³/year	6,124,000
Share of annual effluent treated	%	80
Additional sludge removal	ton DS/y	0
Prefiltration		
Filter type	-	Self-cleaning sand filter and cartridge filters (20 and 10 mu)
Pore size	µm	10
Alternative adsorption media		
Adsorption step		
Type of adsorption material	-	cyclodextrins
Zeolite column diameter	m	11.00
Zeolite/filter bed height	m	1.55
Total required filter surface area	m²	95
EBCT	min	10
Column volume	m³	43.4
Total zeolite/filter bed volume	m³	173.6
Filtration rate	m/h	11
Service life	months	6.8
Service life	bed volumes	20,000
Maximum bed expansion during backwash	%	40%
Expanded filter bed height	m	2.2
Adsorbent material weight	kg/m³	399
Adsorbent material grain diameter	mm	0.2 - 1.5
Sludge production	ton DS/y	
Backwash water		
Backwash water flow	m³/h	49
Backwash time fraction	%	3%
Frequency for all filters combined	number of times/h	0.26
Duration	min	10
Regeneration		
Ethanol concentration	mg/l	70% v/v
Ethanol dosage	kg/h	
Total regeneration duration	h	

Staffing		
Full time equivalents (FTE)	FTE/y	0.5
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/y	205,040
Minimum pumping head for technology	m	2, 6
Energy consumption DEX filter based on GAC	kWh/y	4,999
Energy consumption 8 m pumping head	kWh/y	187,793
Energy consumption backwash water (1%)	kWh/y	12,248

Results based on IPMV criteria for 100,000 PE WWTP at 150 g COD		
		Updated
Parameter	**Unit**	**value 2024**
Removal efficiency micropollutants		
In substream (7/11 NL indicator substances)	%	80 - 95%
In substream (11 NL indicator substances)	%	75 - 90%
In full WWTP + post-treatment (7/11 NL indicator substances)	%	70 - 80%
In substream (EU substances)	%	80 - 95
In full WWTP + post-treatment (EU substances)	%	75 - 85
CO_2 footprint		
CO_2 footprint	g CO_2/m^3 treated	168
CO_2 footprint	g CO_2/m^3 total WWTP	135
Costs (incl. VAT)		
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 treated	0,24-0,37
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 total WWTP	0,20-0,29
Ecotoxicity		
Ecotoxicity reduction	%	

Co-benefits		**Updated**
Parameter	**Unit**	**value 2024**
Additional total N removal	%	20 - 25%
Total N concentration at technology inlet	mg N/l	2.0-2.5
Total N concentration at technology outlet	mg N/l	1.5-2.0
Additional ammonium removal	%	0.67
Ammonium concentration at technology inlet	mg N/l	0.3
Ammonium concentration at technology outlet	mg N/l	0.1
Additional total P removal	%	25 - 33%
Total P concentration at technology inlet	mg P/l	0.3-0.4
Total P concentration at technology outlet	mg P/l	0.2-0.3
Ortho-phosphate concentration at technology inlet	mg P/l	0.1-0.2
Ortho-phosphate concentration at technology outlet	mg P/l	0.1-0.2
Bromide concentration at technology inlet	mg bromide/l	n.a.
Bromate concentration at technology outlet	mg bromate/l	n.a.
Bromate formation relative to influent bromide	%	n.a.
Additional PFAS removal in technology	%	see STOWA 2024-29
Additional disinfection in technology (*E. coli* removal)	reduction factor (log)	neutral
Additional antibiotic resistant bacteria removal in technology	%	see STOWA 2024-30

Technology readiness level (TRL)		
Parameter	**Unit**	**Value**
TRL		5
		The concept still faces early-stage issues, such as backwashing. External regeneration is not yet available, and DEXSORB remains expensive
Outstanding questions (operation / new pilot studies)		Hydraulic optimisation of the system is needed to prevent clogging and avoid media washout during backwashing. The service life needs to be extended to at least 20,000 BV

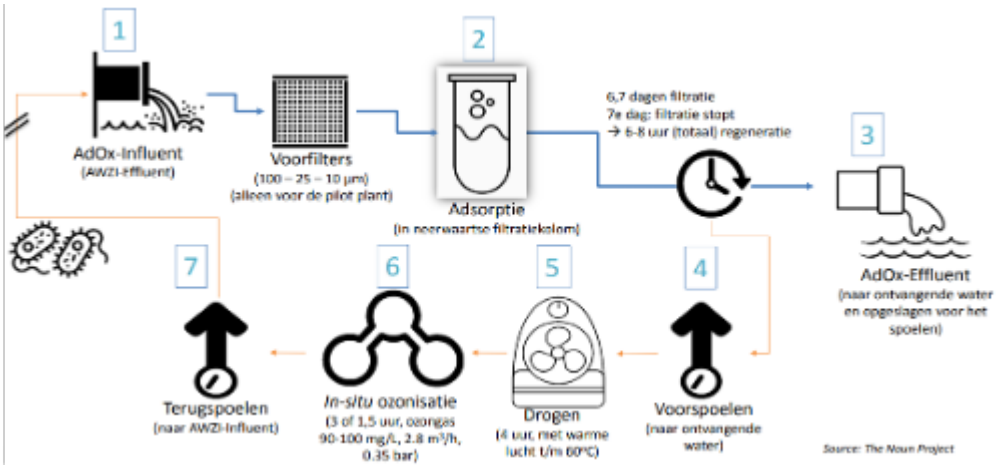
TECHNOLOGY NAME: ADOX

Technology description

AdOx is a adsorption-oxidation process for removal of organic micropollutants. The process uses high-silica zeolites in granular form in a downflow fixed-bed reactor. In this adsorption column, micropollutants are adsorbed from the wastewater. After the adsorption column is saturated, it is regenerated in-situ using ozone gas. As such, removal of a selection of micropollutants is achieved.

There are several expected advantages of combining adsorption with zeolites and in-situ regeneration with ozone: no formation of byproducts and transformation products in the treated WWTP effluent, since no ozone is dosed into the main flow; minimal transport movements due to the in-situ regeneration; and no ozone is used for oxidation of natural organic matter (NOM), because NOM does not adsorb to zeolites.

Process integration schematic (block diagram)



Pilot installation as implemented within the IPMV

Parameter	Unit	Value
WWTP location	-	Leiden-Noord
Period	month/year – month/year	
Pilot pretreatment		Pre-filters
Pilot installation capacity	m^3/h	0,5-1
Tested variations	e.g., dosage in mg PAC/l or g O_3/g DOC	EBCT: 10 & 15 min; flow: 0.5-1 m^3/h
Continuous/batch testing	-	Continuous
Some specific information: e.g., PAC type, O_3 production from air/O_2, bromide concentrations, DOC		Adsorption material: zeolite granules. Production of O_3 from O_2 gas
Analyses conducted		indicator substances, ecotoxicity, bromate, DOC, ARB, PFAS

Design assumptions for full-scale installation

Parameter	Unit	Value
Alternative adsorption media		
Adsorption step		
Type of adsorption material		high-silica zeolite granules
EBCT at DWF design peak	min	10
EBCT at average flow	min	10-15
Filtration rate	m/h	9.68
Surface area per filter column	m^2	5.12
Service life	days	7
Service life	bed volumes	900
Maximum filter diameter	m	5
Filter/zeolite bed height	m	2
Maximum bed expansion during backwash	%	50

Expanded filter bed height	m	3
Adsorbent material weight	kg/m³	590
Adsorbent material grain diameter	mm	2
Sludge production	kg DS/m³ treated	-
Backwash water		
Backwash water type	-	effluent
Backwash water flow	% of incoming flow	4
Backwash time fraction	%	0.3
Frequency for all filters combined		after every 7 days
Duration	min	2x15 (pre-rinse and post-rinse)
Regeneration		
Ozone gas concentration	mg/l	100
Ozone dosage	kg/m³ treated effluent	0.008
Ozonation duration	h	1.5
Ethanol concentration	mg/l	
Total regeneration duration	h	6
Drying column		
Temperature	°C	60
Air flow	m³ air per cycle/m³ filter material	14
Frequency	number of times/year	52
Duration	hours/cycle	4
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/m³ treated	0.14
Minimum pumping head for technology	m	8
Energy consumption 8 m pumping head for adsorption	kWh/m³	0.04
Energy consumption backwash water (4%)	kWh/m³	0.01
Energy consumption drying (in kWh based on natural gas)	kWh/m³	0.05
Energy consumption drying, natural gas	Nm³/m³	0.02
Energy consumption ozonation	kWh/m³	0.04
Production of zeolite used for the calculation of raw material CO_2 footprint	kWh/m³	0.018

Technology design for 100,000 PE WWTP at 150 g COD		
Parameter	**Unit**	**Value**
Technology design		
Selected variant for design elaboration	-	n.a.
Design flow (technology)	m³/h	1,040
Annual volume to be treated with the technology	m³/year	5,365,500
Share of annual effluent treated	%	70
Additional sludge removal	ton DS/y	0
Alternative adsorption media		
Adsorption step		
Type of adsorption material	-	high-silica zeolite
Zeolite column diameter	m	2.29
Zeolite/filter bed height	m	2
Filter surface area per column	m²	4.1
Total required filter surface area	m²	107.4
EBCT	min	10
Column volume	m³	12
Total zeolite/filter bed volume	m³	173
Filtration rate	m/h	12
Service life	days	7

Service life	bed volumes	972
Maximum filter diameter	m	5
Maximum bed expansion during backwash	%	50
Expanded filter bed height	m	3
Adsorbent material weight	kg/m³	590
Adsorbent material grain diameter	mm	2-15
Sludge production	ton DS/y	
Backwash water		
Backwash water flow	m³/h	12
Backwash time fraction	%	6.25
Frequency for all filters combined		after every 7 days
Duration	min	2x15 (pre-rinse and post-rinse)
Effluent storage time in buffer tank for backwash	h	
Regeneration		
Ozone gas concentration	mg/l	100
Ozone dosage	kg/h	30.04
Ozonation duration	h	1.5
O_2 required for O_3 generation	ton/y	71.19
Ethanol concentration	mg/l	
Ethanol dosage	kg/h	
Total regeneration duration	h	6
Drying column		
Temperature	°C	60
Air flow	m³/h/cycle	13
Frequency	number of times/year	1092
Duration	hours/cycle	4
Staffing		
Full time equivalents (FTE)	FTE/y	0.5
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/y	729,694
Minimum pumping head for technology	m	7
Energy consumption 8 m pumping head for adsorption	kWh/y	187,793
Energy consumption backwash water (4%)	kWh/y	42,924
Energy consumption drying (in kWh based on natural gas)	kWh/y	292,790
Energy consumption drying, natural gas	Nm³/y	86,692
Energy consumption ozonation	kWh/y	206,188

Results based on IPMV criteria for 100,000 PE WWTP at 150 g COD		
		Updated
Parameter	**Unit**	**value 2024**
Removal efficiency micropollutants		
In substream (7/11 NL indicator substances)	%	79
In substream (11 NL indicator substances)	%	65
In full WWTP + post-treatment (7/11 NL indicator substances)	%	74
In substream (EU substances)	%	77
In full WWTP + post-treatment (EU substances)	%	72
CO_2 footprint		
CO_2 footprint	g CO_2/m³ treated	102
CO_2 footprint	g CO_2/m³ total WWTP	71
Costs (incl. VAT)		
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m³ treated	0.18-0.26

Annual costs (capital expenditures, maintenance costs and operating costs)	€/m³ total WWTP	0.12-0.19
Ecotoxicity		
Ecotoxicity reduction	%	

Co-benefits		Updated
Parameter	Unit	value 2024
Additional total N removal	%	neutral
Additional ammonium removal	%	neutral
Additional total P removal	%	neutral
Additional PFAS removal in technology	%	see STOWA 2024-29
Additional disinfection in technology (*E. coli* removal)	reduction factor (log)	neutral
Additional antibiotic resistant bacteria removal in technology	%	see STOWA 2024-30

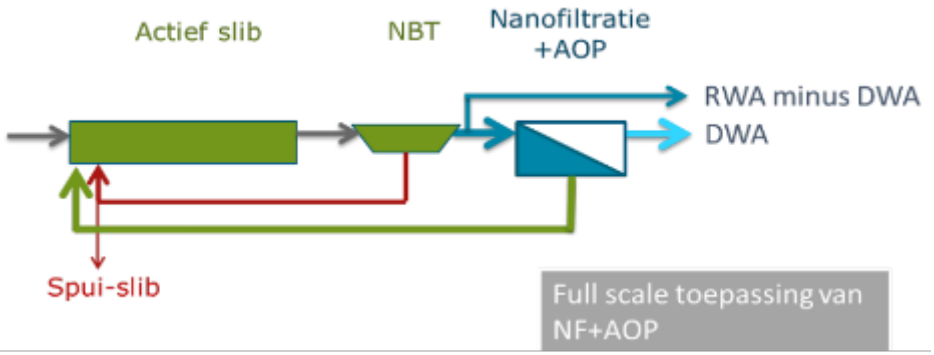
Technology readiness level (TRL)		
Parameter	**Unit**	**Value**
TRL		5
		First pilot was proof-of-principle; a longer running pilot is needed for stable operation before moving on to demonstration scale.
Outstanding questions (operation / new pilot studies)		Removal efficiencies during longer adsorption-regeneration cycles, the strength of the granules under longer-term use, optimisation of the regeneration process, further development of (various types of) zeolite granules, improving drying before regeneration, more efficient use of ozone by recirculation, and aligning zeolite column service life with EBCT

TECHNOLOGY NAME: DIRECT NANOFILTRATION AND UV/PEROXIDE

Technology description

Nanofiltration (NF) is a separation technology. NF membranes are physical barriers with pore openings in the range of 1 to 10 nm. Pathogens and suspended solids can therefore be almost completely separated from water. Larger dissolved molecules, such as humic acids and some micropollutants, are also nearly completely separated. The separated components end up in a concentrate stream, which can then be further treated if required.
Compared to the reference technologies, NF has considerable additional advantages. Because the membrane serves as an absolute barrier, pollutants such as microplastics are retained and disinfection occurs. To further increase removal efficiency, the NF step is followed by post-treatment with UV and hydrogen peroxide. Because the membranes remove 'color components', UV transmittance of the water is significantly increased, enabling UV treatment to be applied efficiently. In addition, this hybrid treatment provides greater robustness in delivering bacteriologically and chemically reliable water at a quality level approaching that of drinking water, thus creating opportunities for high-value reuse. Advantages expected from its use relate mainly to the potential for high-value reuse of WWTP effluent.

Process integration schematic (block diagram)



Pilot installation as implemented within the IPMV

Parameter	Unit	Value
WWTP location	-	Asten
Period	month/year – month/year	April 2021 – October 2022
Pilot pretreatment		Filter for suspended solids removal (200 µm)
Pilot installation capacity	m^3/h	approx. 1
Tested variations		Membranes: DNF 40, 80, 120; UV: 3,000-12,000 J/m^2; H_2O_2: 10-20 mg/l
Continuous/batch testing	-	Nanofiltration: continuous; UV/H_2O_2: only during sampling
Some specific information: e.g., PAC type, O_3 production from O_2, bromide concentrations, DOC		
Analyses conducted		Indicator substances, N, P, SO4, CZV, Ca, Mg, ARB, PFAS, microbiological parameters

Design assumptions for full-scale installation

Parameter	Unit	Value
UV technologies		
Number of UV lamps	number/m^3 treated	1.79E-5
Hydraulic retention time (HRT) UV reactor/tube	min	n.d.
Total UV lamp power	kW/m^3	0.07
Dosage range	J/m^2	6,100
Transmittance	%	95
H_2O_2 dosage	mg/l	15
Prefiltration		
Filter type	-	Amiad
Pore size	µm	200
Organic load concentration in influent	mg/l	n.d.

Organic load concentration in effluent	mg/l	n.d.
Filtration for removal of micropollutants		
Membrane material		Modified PES
Membrane type		DNF80
Pore size	µm	n.a.
Molecular weight cut-off (MWCO)	Dalton	800
Membrane fibre inner diameter	mm	0.7
Membrane surface area	$m^2/m^3/h$	44
Transmembrane pressure (TMP) maximum	bar	6
Membrane flux	$l/m^2/h$	20-30
Cross-flow velocity	m/s	0,5
Recovery	%	75
Filtration cycle (filtration/cleaning)	min/min	59/1
$FeCl_3$ (coagulant)	mg Fe^{3+}/l	n.a.
Type of cleaning agent		NaOH, NaOCl, citric acid
Amount of cleaning agent per year	g/m^3	NaOH: 0.61, NaOCl: 0.40, citric acid: 1.20
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/m^3 treated	0.39
Minimum pumping head for technology	m	0
Energy consumption NF + pre-treatment	kWh/m^3	0.32
Energy consumption UV/H_2O_2	kWh/m^3	0.04-0.07

Technology design for 100,000 PE WWTP at 150 g COD		
Parameter	**Unit**	**Value**
Technology design		
Selected variant for design elaboration	-	n.a.
Design flow (technology)	m^3/h	1,040
Annual volume to be treated with the technology	m^3/year	5,365,500
Share of annual effluent treated	%	70
UV technologies		
Number of UV reactors	Number	2
Number of UV lamps	Number	96
Total UV lamp power	kW/m^3	0.07
UV reactor/tube	m^3	
Dosage range	J/m^2	6,100
Transmittance	%	95
H_2O_2 dosage	mg/l	15
Additional sludge removal	ton DS/y	0
Prefiltration		
Filter type	-	cloth filter
Pore size	µm	200
Organic load concentration in influent	mg/h	n.d.
Organic load concentration in effluent	mg/h	n.d.
Filtration for removal of micropollutants		
Membrane material		Modified PES
Membrane type		DNF80
Pore size	µm	n.a.
Molecular weight cut-off (MWCO)	Dalton	800
Design peak DRF	m^3/h	1,040
Membrane fibre inner diameter	mm	0.7
Membrane surface area	m^2	46,108
Membrane surface area per module	m^2	50
Transmembrane pressure (TMP) maximum	bar	6

Membrane flux	l/m²/h	20-30
Cross-flow velocity	m/s	0.5
Recovery	%	75
Filtration cycle (filtration/cleaning)	min/min	59/1
$FeCl_3$ (coagulant)	kg Fe^{3+}/d	0
Type of cleaning agent		NaOH, NaOCl, citric acid
Amount of cleaning agent per year	kg/year	NaOH 50%: 6,592, NaOCl 15%: 14,313, Citric acid 50%: 12,842
Staffing		
Full time equivalents (FTE)	FTE/y	1
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/y	2,089,069
Minimum pumping head for technology	m	0
Energy consumption pretreatment	kWh/y	43,003
Energy consumption NF	kWh/y	1,670,481
Energy consumption UV/H_2O_2	kWh/y	375,585

Results based on IPMV criteria for 100,000 PE WWTP at 150 g COD		
		Updated
Parameter	**Unit**	**value 2024**
Removal efficiency micropollutants		
In substream (7/11 NL indicator substances)	%	96
In substream (11 NL indicator substances)	%	85
In full WWTP + post-treatment (7/11 NL indicator substances)	%	89
In substream (EU substances)	%	94
In full WWTP + post-treatment (EU substances)	%	85-87
CO_2 footprint		
CO_2 footprint	g CO_2/m³ treated	262
CO_2 footprint	g CO_2/m³ total WWTP	183
Costs (incl. VAT)		
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m³ treated	0.52-0.77
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m³ total WWTP	0.36-0.54
Ecotoxicity		
Ecotoxicity reduction	%	

Co-benefits		Updated
Parameter	Unit	value 2024
Additional total N removal	%	neutral
Additional ammonium removal	%	neutral
Additional total P removal	%	70% (at approx. 0.15 mg/l influent)
Additional PFAS removal in technology	%	see STOWA 2024-29
Additional disinfection in technology (*E. coli* removal)	reduction factor (log)	4
Additional antibiotic resistant bacteria removal in technology	%	see STOWA 2024-30

Technology readiness level (TRL)		
Parameter	**Unit**	**Value**
TRL		5
		NF and UV/H_2O_2 have each been applied at full scale in drinking water production, but not yet on WWTP effluent
Outstanding questions (optimisation / scale-up)		How to manage the concentrate stream?
Outstanding questions (operation / new pilot studies)		

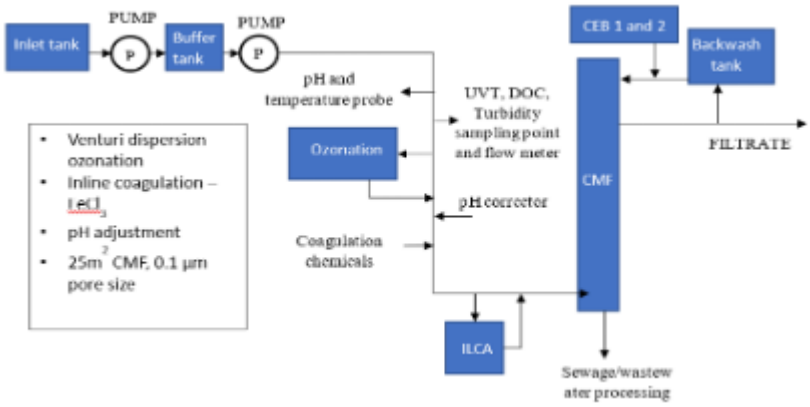
TECHNOLOGY NAME: OZONATION WITH CERAMIC MICROFILTRATION

Technology description

In ozonation with ceramic microfiltration the water is first stripped of micropollutants via ozonation. Depending on the desired effluent quality, this step can be combined with H_2O_2 dosing. It is followed by an in-line coagulation (ILCA) step to optimise the ceramic microfiltration (CMF) for removal of suspended particles, microplastics and bacteria/viruses.

The expected advantage of this technology is the potential for high-value reuse of WWTP effluent.

Process integration schematic (block diagram)



Pilot installation as implemented within the IPMV		
Parameter	**Unit**	**Value**
WWTP location	-	Wervershoof
Period	year	2022 (large pilot)
Pilot pretreatment		none
Pilot installation capacity	m^3/h	5
Tested variations	e.g., dosage in mg PAC/l or g O_3/g DOC	
Continuous/batch testing	-	
Some specific information: e.g., PAC type, O_3 production from air/O_2, bromide concentrations, DOC		11 mg/l DOC, O_3 production from O_2
Analyses conducted		indicator substances, pH, DOC, bromate, PFAS, ARB

Design assumptions for full-scale installation		
Parameter	**Unit**	**Value**
Oxidation with ozone and/or H_2O_2		
O_3 dosage - nominal	g O_3/g DOC	0.6
O_3 dosage - nominal (at 11 mg DOC/l)	g O_3/m^3	6.6
O_3 reactor contact time	min	20
O_3 reactor depth	m	2-6
O_3 input		diffusers or other
H_2O_2	ppm	n.a.
Filtration for removal of micropollutants		
Membrane material		ceramic
Membrane type		ceramic microfiltration
Pore size	µm	0.1
Molecular weight cut-off (MWCO)	Dalton	n.a.
Membrane fibre inner diameter	mm	n.a.
Membrane surface area	$m^2/m^3/h$	n.a.
Transmembrane pressure (TMP) maximum	bar	2
Membrane flux	$l/m^2/h$	n.a.

Cross-flow velocity	m/s	n.a.
Recovery	%	n.a.
Filtration cycle (filtration/cleaning)	min/min	n.a.
$FeCl_3$ (coagulant)	mg Fe^{3+}/l	10
Type of cleaning agent		Sodium hydroxide, sodium hypochlorite, hydrochloric acid, hydrogen peroxide
Amount of cleaning agent per year	g/m³	Sodium hydroxide 50%: 4.7; sodium hypochlorite 15%: 2.2; citric acid 36%: 0.6; hydrogen peroxide 50%: 1.5
Backwash water		
Backwash water flow	% of incoming flow	10
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/m³ treated	0.201
Minimum pumping head for technology	m	3 - 10
Energy consumption coagulation/microfiltration	kWh/m³	0.050
Energy consumption ozonation	kWh/m³	0.096
Energy consumption 8 m pumping head	kWh/m³	0.035
Energy consumption backwash water (10%)	kWh/m³	0.020

Technology design for 100,000 PE WWTP at 150 g COD		
Parameter	**Unit**	**Value**
Technology design		
Selected variant for design elaboration	-	n.a.
Design flow (technology)	m³/h	1,040
Annual volume to be treated with the technology	m³/year	5,365,500
Share of annual effluent treated	%	70
Oxidation with ozone and/or H_2O_2		
O_3 dosage per gram DOC	g O_3/g DOC	0.6
O_3 dosage - nominal (at 11 mg DOC/l)	kg O_3/h	4.0
O_3 dosage - maximum	kg O_3/h	6.9
O_3 reactor volume	m³	347
O_3 production from		oxygen
O_2 consumption for O_3 production	ton/y	354
H_2O_2 dosage	kg H_2O_2/m³	0
Additional sludge removal	ton DS/y	0
Filtration for micropollutant removal		
Membrane material		ceramic
Membrane type		ceramic microfilter
Pore size	µm	0.1
Transmembrane pressure (TMP) maximum	bar	2
$FeCl_3$ (coagulant)	mg Fe/l	10
Type of cleaning agent		Sodium hydroxide, sodium hypochlorite, hydrochloric acid, hydrogen peroxide
Amount of cleaning agent per year	kg/year	Sodium hydroxide 50%: 25,245; sodium hypochlorite 15%: 11,870; citric acid 36%: 2,980; hydrogen peroxide 50%: 7,824
Staffing		
Full time equivalents (FTE)	FTE/y	1
Energy consumption		
Total energy consumption for technology, incl. pumping and backwash	kWh/y	1.078.466
Minimum pumping head for technology	m	3 - 10
Energy consumption coagulation/microfiltration	kWh/y	268.275

Energy consumption ozonation	kWh/y	515.088
Energy consumption 8 m pumping head	kWh/y	187.793
Energy consumption backwash water (10%)	kWh/y	107.310

Results based on IPMV criteria for 100,000 PE WWTP at 150 g COD		
		Updated
Parameter	**Unit**	**value 2024**
Removal efficiency micropollutants		
In substream (7/11 NL indicator substances)	%	86
In substream (11 NL indicator substances)	%	
In full WWTP + post-treatment (7/11 NL indicator substances)	%	80
In substream (EU substances)	%	80-90
In full WWTP + post-treatment (EU substances)	%	75-85
CO_2 footprint		
CO_2 footprint	g CO_2/m^3 treated	239
CO_2 footprint	g CO_2/m^3 WWTP	167
Costs (incl. VAT)		
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 treated	0.71-1.07
Annual costs (capital expenditures, maintenance costs and operating costs)	€/m^3 total WWTP	0.50-0.75
Ecotoxicity		
Ecotoxicity reduction	%	

Co-benefits		Updated
Parameter	Unit	value 2024
Additional total N removal	%	neutral
Additional ammonium removal	%	neutral
Additional total P removal	%	neutral
Bromide concentration at technology inlet	mg bromide/l	
Bromate concentration at technology outlet	mg bromate/l	
Bromate formation relative to influent bromide	%	
Additional PFAS removal in technology	%	see STOWA 2024-29
Additional disinfection in technology (*E. coli* removal)	reduction factor (log)	3,5-4
Additional antibiotic resistant bacteria removal in technology	%	see STOWA 2024-30

Technology readiness level (TRL)		
Parameter	**Unit**	**Value**
TRL		6
Outstanding questions (optimisation / scale-up)		Placement and quantity of H_2O_2 input in relation to ozone dispersion systems to mitigate bromate formation and hydroxyl radical conversion of micropollutants. Performance under stormwater (RWF) conditions (turbidity)
Outstanding questions (operation / new pilot studies)		

APPENDIX 6

COMPARISON OF REMOVAL EFFICIENCY FOR COMBINED TECHNOLOGIES

BACKGROUND

Four removal mechanisms can be distinguished in the IPMV technologies:

- Adsorption
- Oxidation
- Filtration
- Biological degradation

The PACAS, ozonation and GAC reference technologies make use of the first two principles: adsorption or oxidation. The other investigated technologies also use these mechanisms, or a combination of them.

Some of the IPMV investigated technologies combine removal mechanisms to achieve higher removal rates for more of the indicator substances -- also referred to as a 'broader palette' or range of substances. The rationale for combining technologies is that some micropollutants may be effectively removed by one mechanism but not by another. 'Stacking' removal mechanisms, therefore, makes it theoretically possible to achieve higher removal efficiencies for a wider range of substances. This appendix provides substantiation for that rationale.

The analysis draws on the results from the pilot studies, as well as earlier research on PACAS carried out at WWTP Papendrecht (STOWA 2018-02) and information previously compiled on removal efficiencies (Mulder, 2021).

REFERENCE REMOVAL BY PACAS AND OZONATION

A number of the proposed EU indicator substances, specifically, amisulpride, candesartan and clarithromycin, are not generally present in sufficient concentrations in influents and effluents of Dutch WWTPs. This is why these are not included as indicator substances in the Netherlands. The proposed EU indicator substance citalopram does occur in sufficient concentrations, but was excluded as a Dutch indicator substance due to a potentially too high removal in activated sludge (>50%). This does not mean that amisulpride, candesartan and clarithromycin are completely absent in Dutch WWTP influents and effluents. Whether they are present depends on the specific WWTP (Mulder, 2021).

Table B6-1 and B6-2 present the removal of 11 indicator substances with the ozonation and activated carbon reference technologies. These results demonstrate that not all substances are removed equally well by ozonation or PACAS alone; some are removed highly efficiently (>90%) by one or the other technology, while others have lower removals (<80%):

- 1,2,3-benzotriazole, some 4- and 5-methyl-1H-benzotriazoles, and metoprolol are removed more effectively by PACAS than by ozonation.
- Diclofenac, sulfamethoxazole and clarithromycin are removed more effectively by ozonation than by PACAS.
- The removal of irbesartan is comparable for both ozonation and PACAS, at about 50-80%.
- The results for gabapentin are less clear, also considering the results in Table B6-4. Here removal in the WWTP is high, though with PACAS it is low. However, the two tables show lower removal efficiencies by ozonation.
- For some substances, the different sources used to evaluate PACAS removal efficiencies differ by about 10% in reported absolute removal rates. The average removal efficiency across the 11 indicator substances is substantially lower for PACAS at Papendrecht than the values reported by Mulder (2021). The latter also includes, among other things, references to post-treatment PAC.

TABLE B6-1 REMOVAL EFFICIENCY OF 11 NL INDICATOR SUBSTANCES WITH REFERENCE TECHNOLOGIES (OZONATION)*

Substance	Removal in WWTP (%)	Removal in WWTP (average value) (%)	Removal with ozonation (%)	Removal with ozonation (average value) (%)	Removal over entire WWTP with ozonation (average) (%)
Benzotriazole	25-60	43	50 - 70	60	77
Carbamazepine	5-15	10	>80	90	91
Clarithromycin	30-60	45	>80	90	*95*
Diclofenac	10-35	23	>80	90	92
Gabapentin	30-60	45	<50 - 70	50	73
Hydrochlorothiazide	5-25	15	70 - >80	75	79
Irbesartan	5-15	10	50 - 80	65	69
Metoprolol	20-50	35	50 - 80	65	77
Sum of 4-,5-methylbenzotriazoles	10-40	25	50 – 70	60	70
Propranolol	30-80	55	50 - 70	60	*82*
Sotalol	15-35	25	>80	90	93
Sulfamethoxazole	50-80	65	>80	90	*97*
Trimethoprim	30-80	55	>80	90	96
Venlafaxine	5-15	10	70 - >80	75	78
Efficiency '7 out of 11'		40		82	86
Efficiency '11'		27		74	81
Number of substances > 80%		0			5
Number of substances > 70%		0			9

* Source: Mulder (2021).

Notes: green shading indicates values used to calculate the best 7/11; italics are indicator substances from 2018.

TABLE B6-2 REMOVAL EFFICIENCY OF 11 NL INDICATOR SUBSTANCES WITH REFERENCE TECHNOLOGIES (PAC)

Substance	Removal in WWTP (%)*	Removal in WWTP (average value) (%)*	Removal in WWTP Papendrecht (%)**	Removal PACAS pilot Papendrecht at 20 mg PAC/l (%)**	Removal over entire WWTP with activated carbon (average)* (%)
Benzotriazole	25-60	43	64	89	94
Carbamazepine	5-15	10	0	80	78
Clarithromycin	30-60	45	47	*67*	*81*
Diclofenac	10-35	23	67	67	73
Gabapentin	30-60	45	n.d.	nb	81
Hydrochlorothiazide	5-25	15	19	79	92
Irbesartan	5-15	10	n.d.	nb	69
Metoprolol	20-50	35	22	83	94
Sum of 4-,5-methylbenzotriazoles	10-40	25	16	95	93
Propranolol	30-80	55	n.d.	*nb*	*82*
Sotalol	15-35	25	37	85	93
Sulfamethoxazole	50-80	65	n.d.	*nb*	*83*
Trimethoprim	30-80	55	33	100	89
Venlafaxine	5-15	10	n.d.	nb	78
Efficiency '7 out of 11'		40	35	87	91
Efficiency '11'		27	32	74	85
Number of substances > 80%		0	0	6	7
Number of substances > 70%		0	0	8	10

* Source: Mulder (2021), at a dosage of approx. 15 mg PAC/l.

** Source: STOWA 2018-02, for the number of substances exceeding the specified efficiency, missing removal efficiencies were taken from Mulder (2011).

Notes: green shading indicates values used to calculate the best 7/11; italics are indicator substances from 2018.

TABLE B6-3 REMOVAL EFFICIENCY OF EU INDICATOR SUBSTANCES WITH REFERENCE TECHNOLOGIES (PAC)

	Removal in WWTP Papendrecht (%)**	Removal PACAS pilot Papendrecht at 20 mg PAC/l (%)**	Removal over entire WWTP with activated carbon (average)* (%)
Category 1			
Amisulpride			
Carbamazepine	0%	80%	78%
Citalopram			
Clarithromycin	47%	67%	81%
Diclofenac	67%	67%	73%
Hydrochlorothiazide	19%	79%	92%
Metoprolol	22%	83%	94%
Venlafaxine			78%
Category 2			
1,2,3-benzotriazole	64%	89%	94%
Candesartan			
Irbesartan			69%
Sum of 4- and 5- methyl-1H-benzotriazole	16%	95%	93%
2:1 average	39%	82%	89%

* Source: Mulder (2021), at a dosage of approx. 15 mg PAC/l.

** Source: STOWA 2018-02.

Note: green shading indicates values used to calculate 2:1 average.

Comparison of combined PAC and ozonation reference technology

Table B6-4 compares the combination of PACAS and ozonation (PAC + O_3) based on the results of the pilot study at WWTP Leiden-Noord. This was done with target dosages of 7.5 PAC/l and 0.5 g O_3/g DOC. The comparison was made using the PACAS line in the pilot at a low dosage (7.5 mg PAC/l), the ozonation treatment on the non-PACAS line at WWTP Leiden-Noord and the PACAS reference (20 mg PAC/l) from WWTP Papendrecht (see Table B6-2).

Removal in the PACAS line with 7.5 mg PAC/l, at 64% (7/11), was considerably less than the target removal of 80%. In fact, only trimethoprim was almost completely removed, and removal efficiencies for the other substances were ≤70%.

1,2,3-benzotriazole, some 4- and 5-methyl-1H-benzotriazoles, and metoprolol were removed more effectively with PACAS than with ozonation.

From the table a number of conclusions can be drawn:

- To achieve the same removal efficiency with only ozonation or only PAC, a higher dosage is required than for the separate components of PAC + O_3.
- The removal efficiency of ozonation found in this study is comparable to the reference in table B6-1.
- The removal of 7/11 substances is comparable for PACAS 20 mg/l, ozonation (0.5-0.71 mg O_3/mg DOC) and PAC + O_3 (PACAS: 80-85%, PAC + O_3 91% and O_3: 89%) for the scenario of 100% treatment after PACAS (PAC + O_3) and after the WWTP (O_3).
- For ozonation, the average removal across all 11 indicator substances is lower than the average of the best 7/11 substances.
    - Seven substances indeed show similar removal efficiencies with ozonation and PAC + O_3
    - By combining PAC and O_3, the removal of benzotriazole and the sum of 4- and 5-methyl-1H-benzotriazole increases compared to ozonation alone, but it is still not as high as with the 20 mg/l PACAS reference.
    - Metoprolol removal is also higher with the combination than with ozonation alone, and slightly higher than with PACAS alone.
    - Irbesartan removal is higher with the combined technology than with either the ozonation or PACAS reference alone.
    - Diclofenac is removed better with ozonation than with PACAS; on this point, PAC + O_2 is also higher than PACAS.

Based on these results, it can be cautiously concluded that combining O_2 and PACAS achieves higher removal efficiencies for several of the 11 Dutch indicator substances.

TABLE B6-4 REMOVAL EFFICIENCY OF 11 INDICATOR SUBSTANCES: PAC + O_3 FOR SCENARIO AT 7.5 MG PAC/L AND 0.3 O_3 DOSAGE

	PACAS Leiden Noord	PAC + O_{3**}	O_3 reference**	PACAS Papendrecht reference
	7.5 mg PAC/l	7.5 mg/l PAC- 0.33-0.57 g O_3/g DOC	0.5-0.71 g O_3/g DOC	20 mg/l
1,2,3-benzotriazole	57	78	67	89
Carbamazepine	28	89	88	80
Diclofenac	42	98	98	67
Gabapentin	65	79	75	65 (50 – 80)*
Hydrochlorothiazide	53	84	83	79
Irbesartan	42	83	73	65 (50 – 80)*
Metoprolol	71	88	79	83
Sum of 4- and 5- methyl-1H-benzotriazole	55	80	65	95
Sotalol	50	98	99	85
Trimethoprim	95	95	95	100
Venlafaxine	38	78	78	75 (70 - >80)
7/11	64	91	89	87
Average	54	86	82	74
Number of substances >80% removed	1	8	5	6
Number of substances >70% removed	2	11	9	8

* These substances were not measured in the PACAS Papendrecht study. Missing data were therefore drawn from *"Toetsen wijziging gidsstoffen aan 70% reductie"*. Some caution is warranted when combining these values.

** The reported removal efficiencies do not account for the 70% substream and are therefore lower than the total efficiency over the entire WWTP.

Comparison of BODAC – Aurea (BO3)

Table B6-5 compares the removal performance of the ozonation reference with technologies using BACF (BODAC) and the combination of BACF + ozonation (Aurea (BO_3)).

- The dosage reported in the factsheets in appendix 5 assumes 0.3 g O_3/g DOC for Aurea (BO_3). Because this dosage was not measured, surrounding values are also presented in the table.
- The total efficiency over the entire WWTP for ozonation and Aurea (BO_3), at 80-85%, is slightly higher than for BODAC, at 80%. In BODAC, the removal mechanism with the old GAC is bioregeneration, combining adsorption and biological degradation.
- With new GAC, it is primarily adsorption onto the GAC. Compared to use of old GAC, new GAC achieves greater removal of substances that are also effectively removed by PACAS (see above: benzotriazole and the sum of 4- and 5-methyl-1H-benzotriazole).
- With regard to BODAC, the following conclusions can be drawn:
  - The average removal efficiency is lower, which results in a lower removal efficiency across all 11 indicator substances compared to the other technologies examined in this appendix.
  - With the addition of ozonation, removal efficiencies increase in the case of Aurea (BO_3), and the number of substances with a removal efficiency greater than 70% also increases.
- Comparing BACF and ozonation:
  - The substances that are effectively removed with BODAC (sotalol and hydrochlorothiazide) correspond well with those that are effectively removed with ozonation.
  - The 7 best removed substances are the same.
  - The two substances for which ozonation always achieves a lower efficiency, benzotriazole and the sum of 4- and 5-methyl-1H-benzotriazole, have a negative removal with BACF.

  - A striking difference is carbamazepine, which is very effectively removed with ozonation and but has a negative removal with BACF.
- When Aurea (BO_3) is compared with the ozonation reference, a number of conclusions can be reached. Note, however, that it is difficult to make reliable estimates for the individual substances at a dosage of 0.4 g O_3/g DOC and to draw firm conclusions from these. The observations presented below are therefore indicative and based on the average of the two ozone doses presented:
  - The removal efficiencies of benzotriazole and the sum of 4- and 5-methyl-1H-benzotriazole are clearly lower for Aurea (BO_3) than for the ozonation reference.
  - For the other substances, Aurea (BO_3) and the ozonation reference achieve very similar removal efficiencies. BACF alone removes about 7—8 of the 11 indicator substances, with an average efficiency of around 80%. However, the efficiency for 3—4 substances is very low (<30% or even negative). Adding ozonation results in more substances being removed to a greater extent, and total removal is higher than for BACF alone.
  - For 9 of the 11 substances, removal efficiencies are very similar between Aurea (BO_3) and the ozonation reference. The exceptions are benzotriazole and the sum of 4- and 5-methyl-1H-benzotriazole. This means that ozonation alone removes more substances with higher efficiencies and therefore achieves a broader removal palette.

TABLE B6-5 REMOVAL EFFICIENCY OF 11 INDICATOR SUBSTANCES: BODAC, AUREA (BO_3) AND OZONATION REFERENCE

	BODAC residence time approx. 23 min*	BACF in the Aurea pilot**	Aurea (BO_3)**	Aurea (BO_3)**	O_3 reference***	O_3 reference	
	Old GAC	New GAC		0.2 g O_3/g DOC	0.4 g O_3/g DOC	0.5-0.7 mg O_3/mg DOC	****
1,2,3-benzotriazole	-63	67	10	35	60	66	77
Carbamazepine	-7	62	-40	60	98	88	91
Diclofenac	85	80	75	95	97	97	92
Gabapentin	76	70	62	65	85	75	73
Hydrochlorothiazide	79	80	80	86	80	83	79
Irbesartan	30	55	20	60	70	72	69
Metoprolol	68	83	>60	85	90	78	77
Sum of 4- and 5- methyl-1H-benzotriazole	-54	78	-20	20	55	64	70
Sotalol	95	90	85	100	100	99	93
Trimethoprim	74	80	82	100	100	98	96
Venlafaxine	80	70	65	80	90	78	78
7/11	79	83	74	85,9	95	87	86
Average of 11 indicator substances	42	74	44	69,2	84	74	81
Number of substances > 80%	3	6	3	6	8	5	5
Number of substances > 70%	4	8	4	6	9	9	9

* In the BODAC pilot, both old and new GAC were used. The GAC had been in use for years at WWTP Emmen. For the removal efficiency comparison, only the values for old GAC were considered.

** The reported removal efficiencies do not account for the 70% substream and are therefore lower than the total efficiency over the entire WWTP.

*** Source: PAC + O_3 pilot.

**** Source: Mulder (2021); see also Table B6-1.

CONCLUSION

Whether a combination of technologies achieves removal of a wider range of substances (the so-called 'broader palette') depends on which removal mechanisms are combined and whether these are complementary in terms of the removal of individual indicator substances.

One conclusion that can be drawn from this analysis is that combining technologies using adsorption and oxidation achieves higher removal efficiencies (>70% and >80%) for several of the Dutch indicator substances, and therefore a broader removal palette.

When biological conversion in a BACF is combined with ozonation (Aurea (BO_3)), the process achieves a higher removal of more substances than with BACF alone. However, the ozonation reference alone removes more substances at higher efficiencies, meaning that the combination of biological treatment with activated carbon does not result in a broader removal palette.

APPENDIX 7

CO_2-FOOTPRINT DATA INPUT SHEET

STOWA 2025-43 EVALUATION INNOVATION PROGRAMME REMOVAL OF MICROPOLLUTANTS AT WASTEWATER TREATMENT PLANTS

Parameter	Unit		to WWTP baseline	PACAS ref	Ozonation ref	GAC ref	1	2 PACAS Nereda	3 BODAC	4 Bio-GAC + air	5a O3-STEP (no N + P)	5b O3-STEP (incl N+P)	6a UpflowGAC - CarboPlus	6b UpflowGAC - DynaCarbon	7 SF+UV/H_2O_2	8 O_3 + ultrasound	9 PAC + O_3	10 MicroForce	11 Aurea (BO_3)	12 DEX filter	13 AdOx	14 NF + UV/H_2O_2	15 O_3 + ceramic MF
Quantities																							
Incoming wastewater	m^3		7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000
Influent COD	kg		3,831,681	3,831,681	3,831,681	3,831,681	3,831,681	3,831,681	3,831,681	3,831,681	3,831,681	3,831,681	3,831,681	3,831,681	3,831,681	3,831,681	3,831,681	3,831,681	3,831,681	3,831,681	3,831,681	3,831,681	3,831,681
Influent Nkj	kg		359,588	359,588	359,588	359,588	359,588	359,588	359,588	359,588	359,588	359,588	359,588	359,588	359,588	359,588	359,588	359,588	359,588	359,588	359,588	359,588	359,588
Effluent N_{tot}	kg		52,140	52,140	52,140	52,140	52,140	52,140	52,140	52,140	52,140	52,140	52,140	52,140	52,140	52,140	52,140	52,140	52,140	52,140	52,140	52,140	52,140
Removed PE 150 g COD	150 g COD/PE/d		97,225	97,225	97,225	97,225	97,225	97,225	97,225	97,225	97,225	97,225	97,225	97,225	97,225	97,225	97,225	97,225	97,225	97,225	97,225	97,225	97,225
Treated PE in influent 150 g COD	150 g COD/PE/d		100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000
Effluent DOC	mg/l		11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
Design criteria for micropollutant removal																							
Minimum annual post-treatment volume	m^3/year		5,365,500	5,365,500	5,365,500	5,365,500	5,365,500	5,365,500	5,365,500	5,365,500	5,365,500	5,365,500	5,365,500	5,365,500	5,365,500	5,365,500	5,365,500	5,365,500	5,365,500	5,365,500	5,365,500	5,365,500	5,365,500
Annual post-treatment volume treated	m^3/year		5,365,500	7,665,000	5,365,500	5,365,500	5,365,500	7,665,000	5,365,500	6,130,000	5,365,500	5,365,500	6,132,000	6,132,000	6,132,000	5,365,500	5,365,500	6,130,000	5,365,500	6,124,000	5,365,500	5,365,500	5,365,500
Sludge produced	ton dewatered sludge		6,100	6,379	6,100	6,100	6,579	6,379	6,176	6,185	6,100	6,403	6,100	6,100	6,100	6,100	6,172	6,185	6,176	6,100	6,100	6,100	6,100
Sludge dry matter content	%		21.1%	22.1%	21.1%	21.1%	21.6%	22.1%	21.1%	21.1%	21.1%	21.1%	21.1%	21.1%	21.1%	21.1%	21.6%	21.1%	21.1%	21.1%	21.1%	21.1%	21.1%
Sludge produced	ton DS		1,287	1,410	1,287	1,287	1,421	1,410	1,303	1,305	1,287	1,351	1,287	1,287	1,287	1,287	1,333	1,305	1,303	1,287	1,287	1,287	1,287
Transport dewatered sludge	km		100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Transport dewatered sludge	ton		6,100	6,379	6,100	6,100	6,579	6,379	6,176	6,185	6,100	6,403	6,100	6,100	6,100	6,100	6,172	6,185	6,176	6,100	6,100	6,100	6,100
Purchased energy WWTP excluding micropollutant removal																							
Purchased energy																							
Purchased electricity	kWh		1,193,548	1,193,548	1,193,548	1,193,548	1,193,548	1,193,548	1,193,548	1,193,548	1,193,548	1,193,548	1,193,548	1,193,548	1,193,548	1,193,548	1,193,548	1,193,548	1,193,548	1,193,548	1,193,548	1,193,548	1,193,548
Purchased natural gas	Nm^3		3,710	3,710	3,710	3,710	3,710	3,710	3,710	3,710	3,710	3,710	3,710	3,710	3,710	3,710	3,710	3,710	3,710	3,710	3,710	3,710	3,710
Purchased heat	GJ		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Purchased fuel			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diesel	kg		16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000
Purchased energy WWTP for micropollutant removal																							
Purchased energy																							
Purchased electricity	kWh		0	68,985	515,088	4,380	98,571	230,000	223,840	178,201	419,000	419,000	78,244	125,029	6,223,980	518,000	592,724	416,840	253,339	4,999	206,188	2,089,069	783,363
Other influences of post-treatment on WWTP																							
Pumping head	m		0	0	8	8	8	0	22	10	8	8	8	18	8	8	8	8	8	8	8	0	8
Percentage backwash water			0%	0%	0%	1%	5%	0%	1%	1%	1%	10%	0%	5%	1%	0%	0%	1%	1%	1%	4%	0%	10%
Backwash water volume	m^3		0	0	0	53,655	268,275	0	53,655	61,300	53,655	536,550	12,264	306,600	61,320	0	0	61,300	53,655	61,240	214,620	0	536,550
Removal backwash water	m^3		0	0	0	53,655	268,275	0	53,655	61,300	53,655	536,550	12,264	306,600	61,320	0	0	61,300	53,655	61,240	214,620	0	536,550
Purchase of process additives		**Solution**																					
Activated carbon	kg	100%	0	122,640	0	83,200	53,655	122,640	13,333	11,520	31,200	31,200	66,226	66,226	0	0	45,990	0	15,600	9,115	7,626	0	0
Regenerated activated carbon	kg	100%	0	0	0	312,000	0	0	0	0	49,600	49,600	117,734	117,734	0	0	0	0	0	277,278	0	0	0
Activated carbon of biological origin	kg	100%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aluminium chloride, hydrated form	kg	40%	0	0	0	0	0	0	0	0	0	0	0	0	909,580	0	0	0	0	0	0	0	0
Citric acid	kg	50%	0	0	0	0	0	0	0	0	0	0	0	0	7,604	0	0	0	0	0	0	12,842	0
Ferric chloride	kg	40%	260,000	260,000	260,000	260,000	455,076	260,000	260,000	260,000	260,000	621,170	260,000	260,000	260,000	260,000	260,000	260,000	260,000	260,000	260,000	260,000	650,153
Methanol	kg	100%	0	0	0	0	0	0	0	0	0	82,000	0	0	0	0	0	0	0	0	0	0	0
Sodium hypochlorite	kg	15%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14,313	11,870
Sodium hydroxide, membrane process	kg	50%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6,592	0
Sodium hydroxide, production mix	kg	50%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25,245
Polymer, cationic, liquid	kg	100%	23,168	22,556	23,168	23,168	26,280	22,556	23,456	23,492	23,168	24,320	23,168	23,168	23,168	23,168	22,663	23,492	23,456	23,166	23,168	23,168	23,168
Polyaluminium chloride	kg	100%	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200
Hydrogen peroxide	kg	50%	0	0	0	0	0	0	0	0	0	0	0	0	367,920	0	0	0	0	0	0	160,965	7,824
Hydrochloric acid, reaction of propylene and chlorine	kg	36%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2,980
Oxygen (liquid)	kg	100%	0	0	354,123	0	0	0	107,310	0	236,082	236,082	0	0	0	324,613	295,103	289,949	141,649	0	71,194	0	354,123
Materials																							
Reinforced concrete	m^3		3,800	3,875	3,900	4,030	4,000	3,875	4,030	3,800	3,900	4,050	4,030	4,030	4,050	3,800	3,925	4,050	4,050	4,030	3,900	3,800	3,800
Service life reinforced concrete	years		30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30