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Meeting the challenge of emerging contaminants

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Reach out to our experts directly!

Emerging contaminants – do we dare to prioritise?

Pollution by emerging contaminants is one of the most important water quality issues of our time. Our increasing knowledge of water pollution from these new contaminants – and the consequences – is leading to developments of the legal frameworks protecting water quality.

Examples of this are the stricter wastewater effluent requirements and quality criteria for surface water proposed by the European Commission[1,2]. Novel water treatment technologies may help us reach more stringent requirements, but some of these technologies have only been investigated on a pilot scale. Others are in full-scale use by Water Authorities that have begun to tackle the removal of emerging contaminants before effluent discharge.

In this paper, we propose combinations of solutions for sustainable wastewater treatment that address the most important groups of emerging contaminants. We also suggest focus areas for future developments based on scientific knowledge and recent technological advances.

What are emerging contaminants?

We use several terms to refer to different classes of emerging contaminants, which can be grouped according to different criteria. For example, per- and poly-fluoroalkyl substances (PFAS) are classified based on their chemical structure. Another criterion to classify contaminants is their concentration in water, which is the case for micropollutants. Contaminants can also be grouped by their behaviour in the environment, such as Persistent Mobile and Toxic (PMT) substances. Alternatively, emerging contaminants can also be classified based on a specific legal framework, for instance, Substances of Very High Concern (SVHCs).

These terms are context dependent and can overlap to some extent – PFAS can be classified as micropollutants or SVHCs. This paper discusses three groups of contaminants: micropollutants, PFAS, and microplastics (Figure 1).

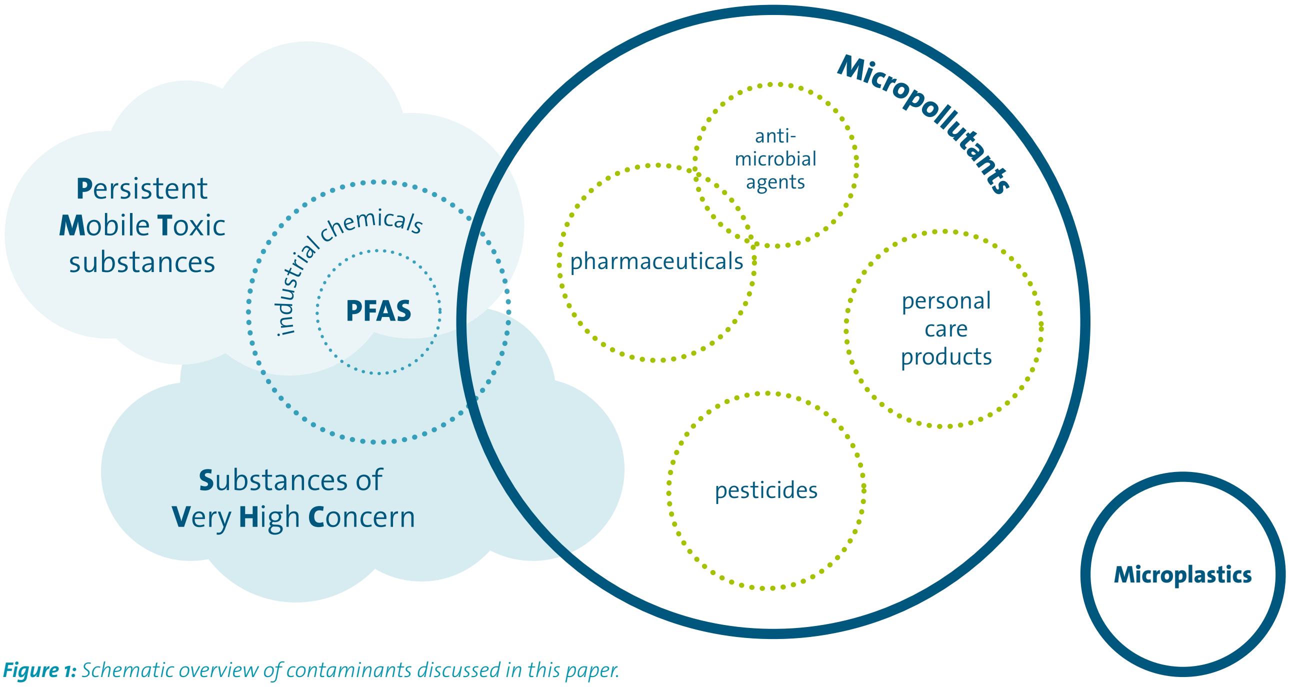


Figure 1: *Schematic overview of contaminants discussed in this paper.*

Contaminants in detail

Micropollutants

Micropollutants are organic contaminants present in wastewater at concentrations measurable in micrograms per litre (µg/L) or less. This group can include pharmaceuticals and their metabolites, industrial chemicals, pesticides, and compounds from personal care products – all of which are now commonly found at low levels in wastewater.

Micropollutants are a broad class of compounds designed for different applications – so they come from various sources and have chemical structures that respond differently to treatment technologies. Micropollutants present a critical challenge in reducing water pollution from treated wastewater.

Improved governance is key to reducing the discharge of micropollutants to wastewater, but end-of-pipe solutions remain necessary given that the release of substances such as pharmaceuticals and personal care products cannot be prevented entirely. These two classes of micropollutants are responsible for most of the toxic load of treated wastewater. They are, therefore, the focus of the recently proposed European Commission directive concerning urban wastewater treatment[1].

PFAS

PFAS are substances with dirt-, grease-, and water-repellent properties used in a wide range of applications. They consist of a hydrophobic tail with a fluorine-rich carbon chain attached to a hydrophilic head.

Short-chain (C4–C8) PFAS have only recently been introduced to the market, as long-chain (>C8) PFAS started to be phased out due to their environmental persistency and toxicity.

These industrial chemicals can be classified as micropollutants since they are detected in wastewater at trace concentrations. However, since PFAS form a group of contaminants with common chemical properties, compared to the broader group of micropollutants, they are dealt with in a separate category. There are several sources of PFAS in the environment; we still need a clear overview of all of them and their relevance. Higher concentrations of PFAS are measured in the wastewater of specific industries, such as pulp and paper production, than in domestic wastewater. This means that PFAS emissions to the environment can be reduced the most by targeting a selection of industrial wastewater streams.

What about inorganic contaminants?

When it comes to water quality and reuse, we know that emerging contaminants are only part of the challenge. Nevertheless, inorganic contaminants, like heavy metals and salts, fall outside the scope of this paper, since the nature and sources of these contaminants, and the technological approaches to remove them, are rather different to those for organic contaminants.

Wastewater treatment plants (WWTPs) still contribute to PFAS emissions to surface water, although to a smaller extent. However, PFAS are present in domestic effluent in such low concentrations and are such inert molecules that the costs and energy demand of available treatment options for domestic wastewater effluent are still prohibitive.

Microplastics

This group of contaminants comprises particles of different polymers, such as polyethylene and polypropylene. Strictly speaking, the term microplastics covers particles smaller than 5 mm and larger than 100 nm, with particles even smaller than that classified as nanoplastics. The main sources of micro- and nanoplastics to the environment are from wear of plastic material, tyres, and paint. Primary sources – plastic particles originally produced in the size range classified as microplastics – include production pellets and scrub particles in personal care products. The discharge of microplastics to the environment from primary sources can be more easily prevented than from secondary sources.

Micro: concentration vs. size

The prefix ***micro*** *in micropollutants and microplastics has different meanings. In micropollutants this prefix refers to the concentration these contaminants occur in water (µg/L or lower). In microplastics, this prefix refers to the size of the plastic particles (µm or smaller).*

Research by the Dutch Foundation for Applied Research (STOWA) concluded that the most cost-effective way of reducing microplastics in WWTP effluent is by optimising their removal in the treatment steps already present at conventional plants[3]. However, less is known about nanoplastics, given the limitations of measurement techniques.

In the next section, we focus on technologies for removing micropollutants and PFAS from water, and not micro- and nanoplastics. However, it is important to highlight that the removal of microplastics in wastewater treatment consists mainly of adsorption to sludge, meaning that the problem is transferred from the water phase to the solids phase. Addressing microplastics earlier in the treatment train or during sludge treatment would reduce the risk of microplastics contamination during resource recovery from sludge.

Antimicrobial resistance

From a wastewater technology perspective, antimicrobial resistance is studied on three different levels:

1. Antimicrobial agents and their metabolites
2. Antimicrobial-resistant bacteria (ARB)
3. Antimicrobial resistance genes (ARGs)

The relationship between these three elements is simple: antimicrobial agents create selective pressure, allowing ARB to thrive. ARB develop resistance traits by acquiring ARGs, and these genes can be horizontally transferred between bacteria if present freely in the environment. Most antimicrobial agents are already classified as micropollutants.

Antibiotics vs. antimicrobial agents

You might be more familiar with antibiotics than with antimicrobial agents. The former are included in the latter, so we'll use the term antimicrobial agents – a broader group that includes not only drugs but also substances such as disinfectants and sanitisers.

The World Health Organization recognises urban wastewater as the main source of ARGs and ARB to the environment, and the European Commission has proposed an obligation to monitor antimicrobial resistance[1] – but no removal targets have been established.

Antimicrobial resistance is a challenge that cannot be solved in wastewater treatment plants alone; much can be gained through governance and measures related to antimicrobial prescription and use. Hence, antimicrobial resistance should not be the main driver when selecting a treatment technology.

Technologies for removal of emerging contaminants

Water treatment technologies can significantly reduce the load of micropollutants, microplastics, and PFAS in the environment. Technologies can be applied to separate a contaminant from water or concentrate it in a smaller volume – or degrade it by physicochemical or biological processes (Figure 2).

If a WWTP applies a separation/concentration technology, it must follow this with a degradation step unless the concentrated stream is landfilled, incinerated, or recycled.

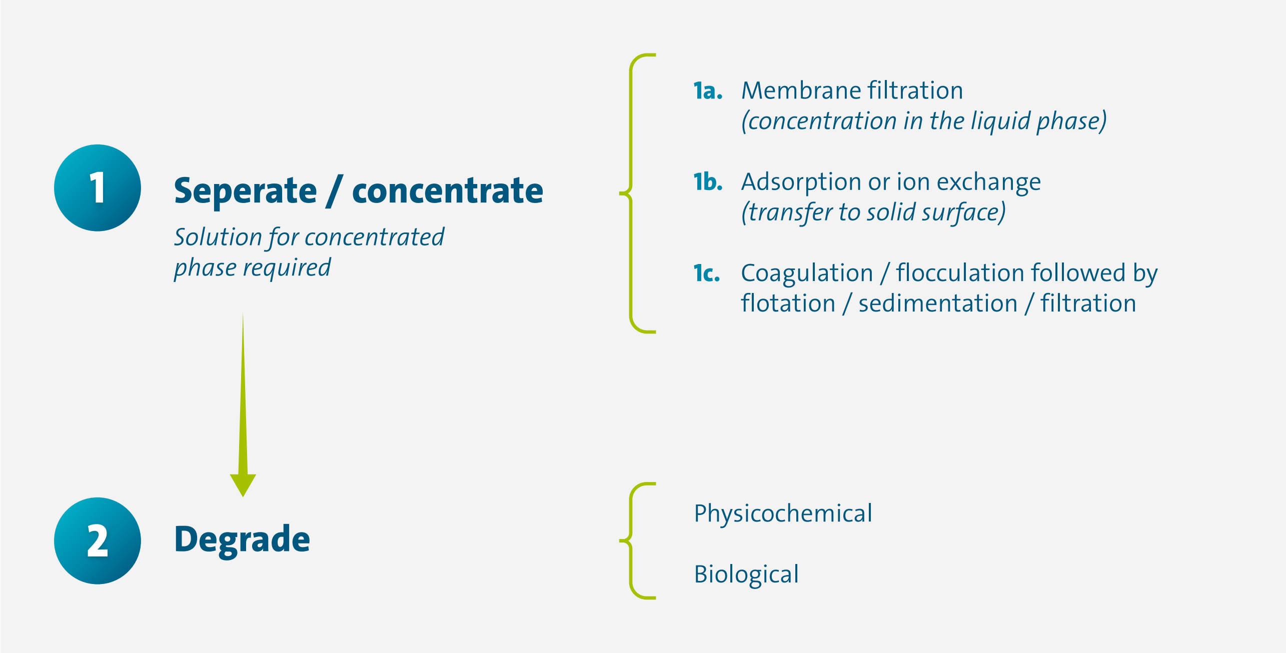
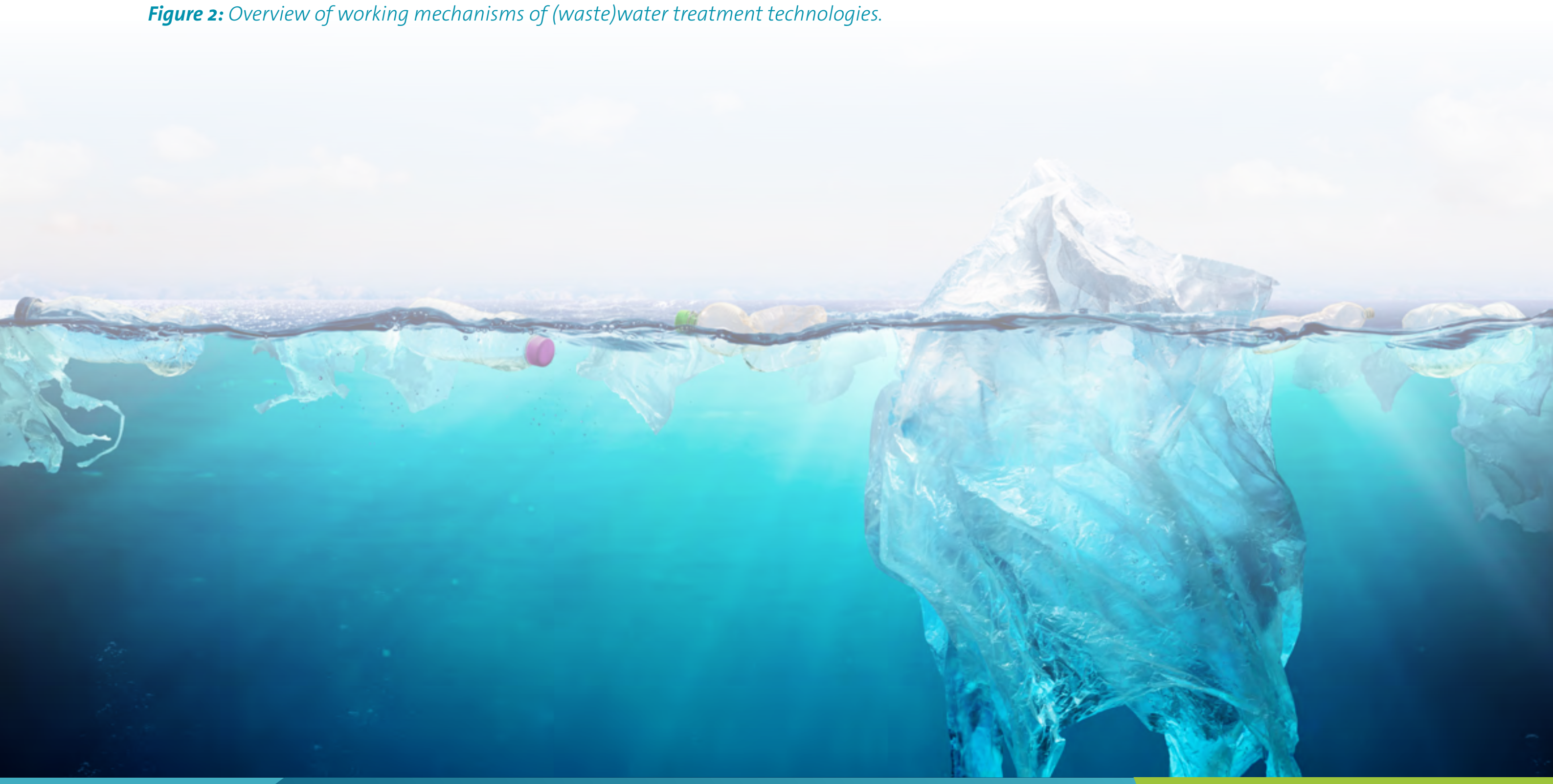


Figure 2: *Overview of working mechanisms of (waste)water treatment technologies.*



Separation technologies

We can divide the separation technologies into three groups of processes (Figure 3):

1. Adsorption or ion exchange-based technologies
2. Membrane filtration
3. (Electro)coagulation/flocculation followed by flotation/sedimentation/filtration

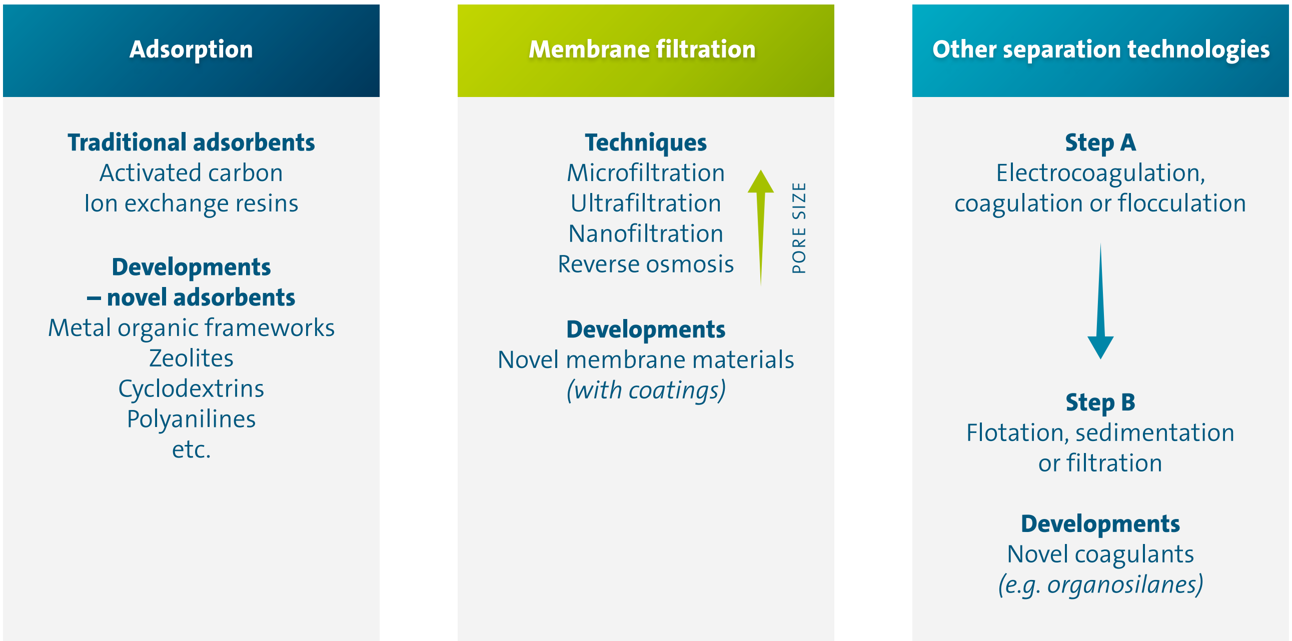


Figure 3: *Overview of separation technologies.*

Adsorption technologies based on activated carbon are currently one of the most suitable options for the removal of a wide range of micropollutants. These technologies are applied in several projects within the Innovation Program Removal of Micropollutants at Wastewater Treatment Plants (IPMV) at STOWA. They are also effective, but to a lesser extent, for PFAS removal. The main bottleneck of these technologies is related to the replacement or regeneration of activated carbon. Finding renewable sources for producing activated carbon, or minimising the dose of powdered activated carbon (PAC) or the reactivation frequency of granular activated carbon (GAC), will contribute to reducing the costs and carbon footprint of these technologies.

Ion exchange (IEX) resins are less effective for micropollutants removal, given that micropollutants include neutral molecules, as well as positively and negatively charged species. Nevertheless, since PFAS are normally negatively charged, IEX is currently one of the most effective technologies for removing them from water. Bottlenecks of IEX include the replacement or regeneration of saturated resin, removal of undesired salts, and a change in the pH of the treated water, given the poor buffering capacity of wastewater.

Membrane-based technologies can be divided into four groups depending on membrane pore size. Micro and ultrafiltration membranes are unsuitable for micropollutants and PFAS removal due to their relatively large pore size. Nanofiltration and reverse osmosis (RO) membranes are more suitable for micropollutants and PFAS removal. However, they are not the most cost-effective options due to their high energy requirements, production of a concentrated stream, and, in the case of RO, the undesired removal of salts.

Technologies based on coagulation, electrocoagulation, or flocculation – followed by a separation step – are not effective for micropollutants removal but are being investigated and developed for PFAS and microplastics removal.

Degradation technologies

Micropollutants degradation can occur via physicochemical (chemical oxidation and reduction) or biological processes (Figure 4). PFAS can also be degraded in physicochemical processes, although the stability of these chemicals makes their degradation energy-intensive, and further development is needed to make this process cost-effective.

Chemical oxidation

Sources of oxidising power:

- ✓ Light *(e.g. UV)*
- ✓ Ultrasound
- ✓ Chemical *(e.g. H_2O_2; O_3)*
- ✓ Electricity
- ✓ Heat
- ✓ Electrons *(e-beam)*
- ✓ Plasma

Mostly used in combinations *(more than one source)* and with catalysts

Chemical reduction

Relevant for PFAS

Sources of reducing power:

- ✓ Chemical *(e.g. SO_3^{2-})*
- ✓ Electrons *(e-beam)*

Biodegradation

- ✓ Suitable for a fraction of micropollutants
- ✓ Greatly contributes to removing background dissolved organic matter

Figure 4: *Overview of degradation technologies.*

Chemical reduction technologies are emerging as an alternative for defluorinating PFAS and the treatment of contaminants containing other halogenated groups, such as iodinated or chlorinated chemicals. These technologies are still in development and not yet applied at full scale.

Biodegradation requires a lower energy input than physicochemical processes, resulting in lower costs and a smaller carbon footprint. However, the biodegradation rate for several micropollutants is not high enough to achieve significant removal in the typical retention time for wastewater treatment. As a result, biodegradation technologies need to be combined with alternatives based on chemical oxidation or adsorption.

Nevertheless, biodegradation is still a strong ally in micropollutants removal, mainly for removing dissolved organic matter from the water matrix. Since the dissolved organic matter in wastewater interferes with most technologies that target micropollutants, biodegradation can reduce dissolved organic matter concentrations, increasing the efficiency and sustainability of downstream technologies. This combination of biodegradation followed by ozonation has been successfully tested within the IPMV.

Oxidation technologies rely on different oxidising agents, such as ozone and hydrogen peroxide, often in combination with ultrasound or in the presence of UV light as a catalyst. However, UV light treatments are energy intensive for streams with relatively low transmittance, such as wastewater effluent. Still, they become a more viable option if water transmittance is improved by upstream steps, such as nanofiltration.

Ozonation is a cost-effective technology already applied to full-scale micropollutants removal. However, two important drawbacks of ozonation are the energy required for ozone production and the formation of bromate, a toxic ion produced by the reaction of ozone with bromide ions naturally occurring in water.

Bromate formation during ozonation may not be a showstopper depending on the threshold established for bromate concentration in surface water. However, the application of ozonation for micropollutants removal can be limited if thresholds with a large safety factor are applied based on bromate's human toxicity – and not its toxicity for aquatic organisms.

Even so, ozonation can be combined with other removal processes to address bottlenecks. Since dissolved organic matter concentration is the driver of ozone doses applied to remove micropollutants from wastewater, reducing organic matter concentration significantly contributes to reducing the absolute ozone dose. Combining ozonation with other technologies based on different removal mechanisms also reduces the relative ozone dose – and bromate formation – and targets a broader spectrum of contaminants.

Ozonation processes degrade contaminants either by direct oxidation by ozone or indirect oxidation by radicals formed in the reaction of ozone with dissolved organic matter. Ozone only reacts with specific groups of molecules, whereas radicals react less selectively – making it a side-effect of ozonation rather than the ultimate goal. In other oxidative technologies, radical formation is the goal, so the question of whether we should be focusing on the formation of radicals or not is important to determine the direction of future developments in oxidation technologies.

The way forward

How far should we go to remove emerging contaminants from wastewater? Increasingly complex treatments can help remove emerging contaminants, but they come with higher energy consumption, and sometimes also chemical consumption.

The recently proposed European directive concerning urban wastewater treatment[1] establishes guidelines and targets to ensure that the removal of micropollutants from wastewater is done in a cost-effective way. Similar strategies for PFAS and microplastics are expected in the near future and should rely heavily on governance aspects, given the relevance of diffuse or indirect sources of these contaminants.

Setting directions and defining a toolkit for microplastics and PFAS removal

When it comes to detecting PFAS and microplastics – and removing them from water – size matters; the smaller the molecule or particle, the more difficult it is to measure and remove it. For this reason, microplastics research often doesn't address nanoplastics, and removal technologies are less efficient for nanoplastics and short-chain PFAS. The water industry requires developments in monitoring methods to better understand the extent of water pollution with these contaminants and to define where the most cost-effective measures can be implemented.

PFAS are a particularly challenging group of contaminants due to their high stability; discontinuing their use is the best way to reduce environmental contamination. Nevertheless, as these pollutants are already circulating in our environment, there's an urgent need to further develop technologies to remove them from water in a cost-effective and sustainable way.

A circular economy requires a focus on biosolids

The fate of contaminants such as long-chain PFAS and microplastics in wastewater treatment is mostly adsorption to biosolids or sludge. From a water perspective, we can talk about removal, but from a circular economy perspective, the term "removal" is misleading since the accumulation of certain contaminants in biosolids can hinder resource recovery from sludge. Sludge treatment technologies should focus on the complete removal or immobilisation of contaminants so that the nutrients contained in sludge can be recirculated without threatening ecological health.

Implementing post-treatment technologies for full-scale micropollutants removal

Micropollutants removal at WWTPs is expected to be mandatory in the EU in the near future[1]. Given that micropollutants are a chemically heterogeneous group of contaminants, WWTPs should aim for a combination of technologies that use different removal mechanisms to target a broad spectrum of compounds. Additionally, making use of biological processes is a cost-effective way to increase the efficiency and sustainability of most technologies by removing biodegradable micropollutants and reducing organic matter concentrations.

To ensure we get maximum benefit from limited resources, it may be necessary to prioritise which emerging contaminants to remove from the water cycle so we can employ the most cost-effective strategies, for example, prevention instead of treatment. Prioritisation has already started with the proposal for European regulation on micropollutants removal from wastewater effluent. For other contaminants, lack of both knowledge and technology is delaying decision-making. Moving forward requires well-coordinated programs to fill these gaps so that we can guarantee a clean water cycle for generations to come.

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About Royal HaskoningDHV

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For more information visit our website:

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References

[1] Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL concerning urban wastewater treatment. 2022/0345 (COD).

[2] Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) and Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste.

[3] STOWA, Verkenning van verwijderingsroutes microplastics in de RWZI, 2021-51.