



Existing and emerging technologies for microplastics removal from wastewater and stormwater

Summary of the FanpLESStic-SEA project activity

A3.1 *State-of-the-art microplastics removal technologies*

FanpLESStic-sea project 2021

Introduction

This document “Existing and emerging technologies for microplastics removal from wastewater and stormwater” is a summary based on a report on the same topic (Existing and emerging technologies for microplastics removal) being both outputs of Activity 3.1 *State-of the-art microplastic removal technologies* in the [FanLESStic-sea project](#), led by the Natural Resources Institute Finland (Luke) aiming to identify and validate state-of-the-art microplastic removal technologies and develop and refine new solutions.

The full report can be found [here](#).

The “FanLESStic-sea project – Initiatives to remove microplastics before they enter the sea” is an Interreg project co-funded project where HELCOM is partner.

Existing and emerging technologies for microplastics removal from wastewater and stormwater

The problem

Today, the knowledge on microplastics (MPs, polymer particles less than 5 mm in size) is still limited: especially their presence, pathways and exposure effects on human health and the environment. Research on the occurrence of MPs in the environment started only recently and standardized analysis methods are still under development which makes the comparison of results very difficult (Simon et al. 2018, Borg Olesen et al. 2019).

Microplastics in the environment are composed of the originating plastic polymers and the eventual additives. In addition, other compounds, such as POPs (persistent organic pollutants) may have been adsorbed on the surfaces of the particles which may cause negative impacts on organisms (Andersson-Sköld et al. 2020). Thus, their ending in the environment is also to consider all these chemical compounds. Overall, plastic polymers are known to be very persistent in the environment. However, since the production of plastics started around sixty years ago, their perdurability in the environment is unknown (Andrady & Neal 2009).

Even though degradation of plastic polymers in the environment is slow, it is gradually happening by the effect of sunlight, rain, wind, and biological breakdown (Scalenghe 2018). Ward et al. (2019) suggest that plastic in the environment may be more susceptible to degradation than previously recognized and that sunlight, rather than microbes, has the most important role in the degradation.

This policy brief presents existing and emerging technologies, and methods for MPs removal especially from urban aquatic environments (Vahvaselkä & Winqvist 2021). In recent years, physical, chemical, and biological technologies and methods for MPs removal have been investigated and developed. Filtration-based technologies include sand and disc filters, biofilters, membrane bioreactors and ultrafiltration methods. Coagulation and flocculation, electrocoagulation and sol-gel induced agglomeration are chemical methods investigated for MP removal. Methods based on activities of microorganisms, higher marine organisms and plants are also briefly discussed.

Sources of microplastics

Microplastics, polymer particles less than 5mm in size, are often categorized as primary (microplastics that are purposely manufactured in microscopic size to carry out a specific function) or secondary microplastics (representing the results of wear and tear or fragmentation of larger plastic items) (GESAMP 2016). It is estimated that the largest share of MPs originates from secondary sources (Lassen et al. 2015). Moreover, due to the microplastic restriction proposal for intentionally added MPs considered by the European Commission, the share of primary MP sources is expected to decrease even more in the EU (ECHA 2021). The most important identified sources of secondary MPs are traffic (tyre and break wear particles, road markings), building paints, clothing, artificial turf, pellets from plastic industry, fishing gear and marine paints (Eunomia & ICF 2018).

Substantial amounts of MPs are transported into and retained in wastewater treatment plants (WWTPs). In general, MPs particles are efficiently removed from wastewaters during wastewater treatment. However, as WWTPs receive variable volumes of MP-containing wastewaters, these treatment processes are in the need for further optimization to retain MPs even more efficiently.

Stormwaters also contain significant amounts of MPs. However, most stormwaters end up in aquatic environments either untreated or only partially purified; especially traffic related MPs are transported in stormwaters and may end up in surface waters and soil untreated (Baresel & Olshammar 2019,

Bollmann et al. 2019, Pankkonen 2020, Winqvist et al. 2021). To the best of our knowledge, the retention of stormwater MPs has been the subject of a limited number of studies mainly based on sedimentation and filtration.

Sewage sludge is also a source of MPs, since 69 – 99% of MPs in wastewater is transferred to sewage sludge during wastewater treatment (Sun et al. 2019). If sewage sludge is used as soil amendment without further treatment, MPs can migrate to ground water or be taken up by the plants (Gao et al. 2020). Moreover, treatment methods of MP-laden matrices (e.g. sewage sludge, pond sediments, sand, plant biomass, membrane retentate) created with MP retainment processes are lacking in general.

Upstream measures to address microplastics

Microplastics can be addressed either with upstream measures to prevent the release to the environment or if already released, by using different removal technologies to remove them. This summary concentrates on the removal technologies, however, the on-going work at EU level is to be mentioned as an example of upstream measures.

In 2019, upon request from the European Commission, the European Chemicals Agency (ECHA) proposed an EU restriction on intentionally added microplastics in products and the restriction is to be adopted in 2021 or 2022, if agreed by the European Commission and EU member states (ECHA 2021). Since this restriction concerns only primary microplastics, the EU is preparing a consultation on measures to reduce microplastics pollution from secondary sources (including car tyres), thus addressing both intentional and unintentional sources of microplastics. The consultation, which is planned for the third quarter of 2021, is to focus on labelling, standardization, certification, and regulatory measures for the main sources of these plastics (EC 2021).

In addition to the above-mentioned EU regulatory measures, there are examples of other preventive methods. One of the largest sources of microplastics in a city is laundry. Therefore, filters to laundry machines could be one important way to reduce the polyester fibres entering the wastewater stream. A study showed that a filter would capture 65% of polyester fibres (Browne et al. 2020). Unfortunately, research conducted in this field is very limited and therefore, scarce information is available.

Removing microplastics from wastewater and stormwater

In recent years, several physical, chemical and biological methods for microplastics (MPs) removal have been investigated and technologies developed with MP removal efficiencies reported higher than 90%. Filtration-based technologies include sand and disc filters, biofilters, membrane bioreactors and ultrafiltration methods. Coagulation/flocculation, electrocoagulation and sol-gel induced agglomeration are chemical methods investigated for MP removal. There are also potential methods based on activities of micro-organisms, higher marine organisms, and plants.

Wastewater and microplastics

In wastewater treatment, organic matter and solid particles are removed from wastewater. A simplified flow chart within European WWTPs with various treatment steps: pre-treatment, primary, secondary and tertiary treatments is shown in Figure 1. The treatment processes consist of physical, chemical and biological methods to meet the quality requirements for effluents discarded to the aquatic environment (Norén et al. 2016, Sun et al. 2019) (see Figure 2).

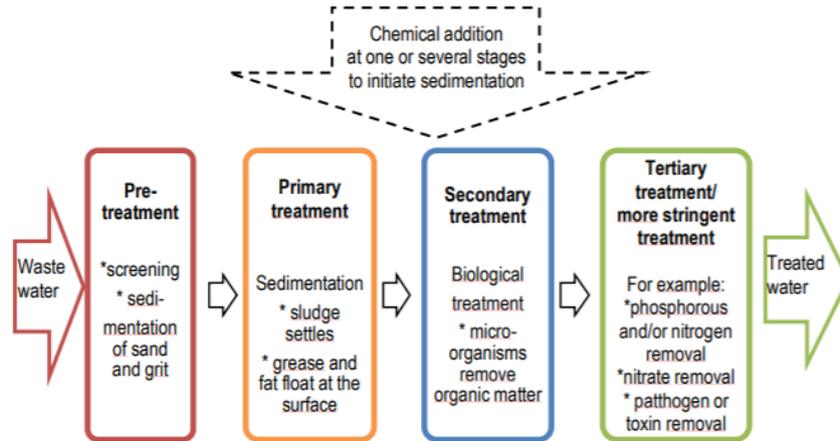


Figure 1. A general overview of treatment steps in wastewater treatment plants (Norén et al. 2016).

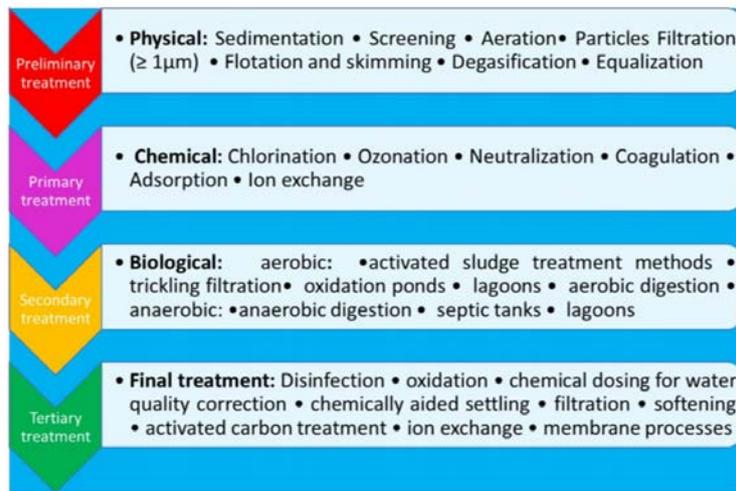


Figure 2. Classification of wastewater treatment methods (Poerio et al. 2019).

The treatment steps and technologies in wastewater treatment were not specifically designed to remove MPs from the wastewater (Norén et al. 2016, Sun et al. 2019). However, in recent years it has been recognized that municipal and industrial wastewaters contain variable levels of MP particles highlighting the role of WWTPs in MP control. Therefore, the fate of MP in wastewater treatment processes is of great interest (see Figure 3). According to recent studies, the concentrations of MPs in influents and effluents of WWTPs are in the range of 1 – 18 000 and 1 – 450 MP particles/litre, respectively (Talvitie et al 2017b, Simon et al. 2018, Sun et al. 2019). In general, WWTPs with tertiary treatment processes yield a lower MP concentration in the effluent than those with only primary or secondary treatment processes. The large variations in MP concentrations in WWTPs could be partially related to differences in sample collection, pretreatment and analysis methods applied. For example, a higher MP concentration might be observed when a finer mesh size is applied in sampling (Simon et al. 2018).

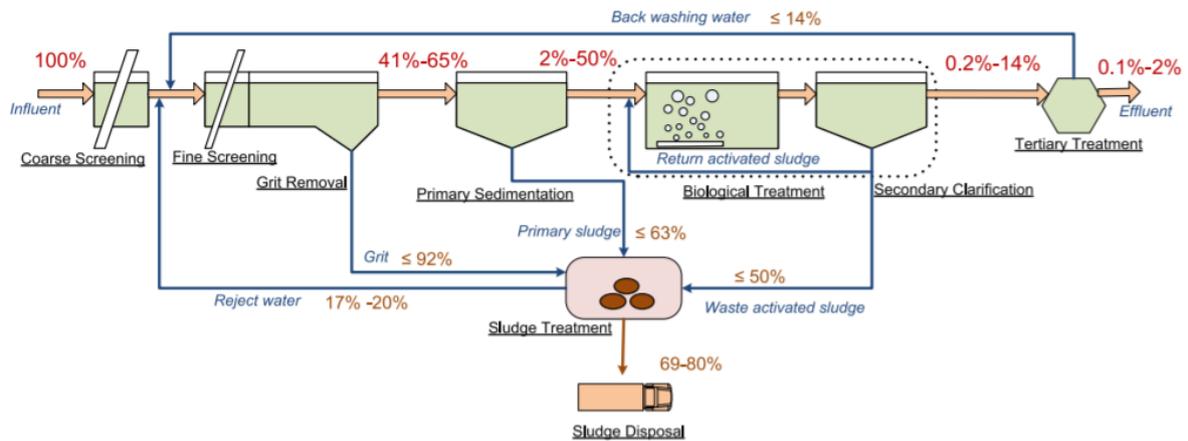


Figure 3. Estimated microplastic particle flow in wastewater treatment plants with primary, secondary and tertiary treatment processes (Sun et al. 2019).

The reported MP removal efficiencies vary between 88 – 99.9% (Sun et al. 2019). An average removal efficiency for MPs of 93% in the WWTPs of the Baltic Sea Region was estimated by Baresel & Olshammar (2019).

According to Sun et al. (2019), the tertiary treatment may provide substantial additional polishing on microplastics removal. Overall, microplastics concentration in the effluent further decreased to 0.2%–2% compared to the influent after the tertiary treatment. However, there are also studies showing that the tertiary treatment, biologically active filter (BAF) did not decrease the microlitter concentration in the effluent (Talvitie et al., 2017b). Microplastics removal efficiency hence depends on the treatment processes applied, with the membrane related technologies showing the best performance. Similar results were obtained by Talvitie et al. (2017a) (see Figure 4) who compared the removal efficiency of different tertiary treatment processes; disc filter (DF), rapid sand filtration (RSF) and dissolved air flotation (DAF) treating secondary effluent, in addition to membrane bioreactor (MBR) treating primary effluent. MBR provided the highest removal efficiency (99.9%), followed by RSF and DAF, with a removal efficiency of 97% and 95%, respectively. The removal efficiency of DF varied from 40% to 98.5%. Similarly, according to Sun et al. (2019) in the survey conducted in WWTPs in New York, two plants with membrane filters did not release microbeads while four other plants with different advanced filter (i.e. a rapid sand filter, a continuous backwash filter and two filters with unspecified type) did.

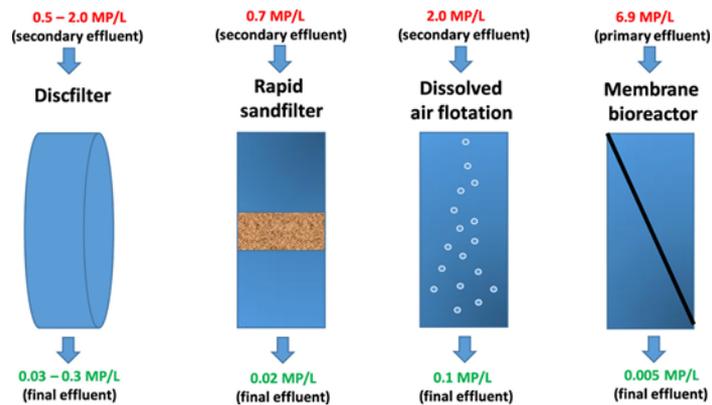


Figure 4. The efficiency of different tertiary and secondary (MBR) treatment techniques (removal rates: DF 40–98.5%, RSF 97%, DAF 95% of the microplastics (MPs) from secondary effluent; MBR decreased 99.9% of the MPs from primary effluent providing also the lowest MP concentration in the final effluent) (Talvitie et al. 2017a).

Wastewater treatment plants are efficient in removing microplastics. However, after the three-step main treatment, it is possible to add a so-called polishing step. This polishing aims at retaining various pollutants, not only microplastics. The technologies used are chosen to remove a palette of pollutants not a single one. Possible processes include filtration, sedimentation, oxidation, and sterilization, the two latter ones being the most efficient towards plastic. These technologies can range from simple polishing ponds (big ponds where the water is allowed to settle further for some days) to nano-filtration membranes.

Based on this, there are some factors that influence the cost-effectiveness of the applied technologies. As an example: a WWTP is in the countryside where land is cheap. A polishing pond is a very good and affordable solution if polishing treatment is needed. In addition, the pond can act as a buffer in case there are issues at the WWTP (such as overload, malfunction, etc.). However, a WWTP located in a central area where there is also a high demand for phosphorous, a rapid sand filter or a rotating drum system could be a better technology to be implemented.

Stormwater and microplastics

Existing stormwater management technologies for removal of solid particles and pollutants include wet and dry stormwater retention ponds, infiltration basins, constructed wetlands, and various filtration systems (Liu et al. 2019a, Andersson-Sköld et al. 2020, Pankkonen 2020, Vogelsang et al. 2020). Data on the efficiency of these methods of MP particles removal is, however, limited (Monira et al. 2021). In recent years, the fate of urban and highway stormwater MPs in sedimentation ponds, (bio)filters and bioretention systems was studied (Borg Olesen et al. 2019, Pankkonen et al. 2020, Kuoppamäki et al. 2020, Lange et al. 2021, Monira et al. 2021, Smyth et al. 2021). Borg Olesen et al (2019) found that MP retainment efficiency of a pond in Denmark was roughly estimated to be 85%, which is similar to the general treatment efficiency for particulate matter in retention ponds. Therefore, stormwater retention ponds seem to be important sinks for MPs (Borg Olesen et al. 2019).

Ecologically based designs, such as biofilter structures and solutions are increasingly investigated for stormwater.

The efficiency of a bioretention cell in MP removal from a parking lot runoff has recently been studied in a two-year study in Canada, where an 84% decrease in the median MP concentration in the 100 – 5000 μm range was reported (Smyth et al. 2021).

Pankkonen (2020) studied MP removal efficiency of two filtration media in a separate stormwater sewer network in Helsinki, Finland. A concrete-based filtration system with either sand (grain size 0.8

to 1.2 mm) or biochar (grain size 5 – 50mm) was used to filtrate stormwater during rain events. According to the results, sand filtration removed up to 96% of MPs from stormwater runoff and biochar filtration 93%.

Further upstream, street dust contains potentially high amounts of MPs, especially tyre and bitumen MP particles. Therefore, regular street sweeping might prevent transport of these MPs via stormwater out in the environment (Järnskog et al. 2020, Fältström & Anderberg 2020).

Future potential: biological methods

Potential methods for MP removal based on activities of microorganisms, higher marine organisms and plants have recently been investigated. Micro-organisms that are capable of MP degradation have been identified, although the reported rates of degradation have been low. Different viscous gels and mucus produced by microbes and higher marine organisms can efficiently trap or bind MP particles. This makes them potential candidates for alternative solutions as biofloculants for example in wastewater treatment (Cunha et al. 2020). However, further research and development is needed for industrial applications.

Information on the uptake and accumulation of MPs by higher plants is still limited but increasing. Plants take up and accumulate MPs in their roots and subsequently transport them from the roots to other parts of the plant. This can be monitored using fluorescent microbeads (Ebere et al. 2019, Li et al. 2020). The efficiency of vegetation-based methods for retention of especially small size MPs and nanoparticles in stormwaters should be further demonstrated.

Comparison of different MP removal technologies and methods

The comparison of literature data on MPs concentrations and removal efficiencies by various technologies can be problematic mainly because sampling methods differ, different analytical approaches have been used for quantification of MPs and because the lower size limit of detection and quantification varies between studies. Also, the majority of studies report MPs in terms of particle number per unit volume, which makes it difficult to compare the results as MP particles break up and fragment over time. Particle numbers are important when assessing the environmental impacts of MPs, but this measure is insufficient when assessing the efficiency of treatment methods. There, the mass of MPs, as a conserved quantity, is to be used (Simon et al. 2018, Borg Olesen et al. 2019, Poerio et al. 2019).

An overview of existing and emerging technologies and methods for MP removal is presented in Table 1. MP concentrations are presented in the units reported in the original studies, almost exclusively as MP particle numbers per volume.

Table 1 Comparison of various microplastics (MPs) removal technologies and methods (Vahvaselkä & Winquist, 2021, modified from Padervand et al. 2019, Zhang et al. 2021).

Method	MPs removal efficiency (%)	Comments	Selected references
Sand filtration	74 – 97	Simple operation, low cost. May be ineffective for small particles.	Talvitie et al. 2017a, Bayo et al. 2020, Pankkonen 2020
Disc filtration	40 – 99	Relatively low energy consumption. Filter cloth clogging.	Talvitie et al. 2017a, Simon et al. 2019
Membrane bioreactors	Up to 100	Very high MP removal efficiencies obtained, produces a high-quality effluent, high volumetric loading, low sludge yield which reduces sludge handling and disposal costs.	Talvitie et al. 2017a, Lares et al. 2018, Bayo et al. 2020, Baresel et al. 2019

		Membrane fouling, high energy consumption.	
Conventional activated sludge	91 - 98	Robust, cost-effective, flexible, treating a wide range of influent concentrations. Long retention times, high cost of energy and the processing and disposal of sludge.	Lares et al. 2018, Baresel et al. 2019
Dynamic membranes	Not available	Low cost, easy cleaning, low energy consumption. Tested only for microparticles other than MPs.	Li et al. 2018
Coagulation	17 - 99	Suitable for the removal of small MPs, controllable operational conditions, simple mechanical devices, low energy consumption. Large quantities of chemicals needed, non-applicable for large MPs, bulky sludge volume.	Ma et al. 2019a, b, Rajala et al. 2020
Electrocoagulation	99	Suitable for the removal of small MPs, energy efficient, cost-effective, flexible to automation, does not require chemical coagulants, less sludge. Repeated need of replacing the sacrificial anode, cathode passivation.	Perren et al. 2018
Sol-gel agglomeration	99	Alternative for traditional flocculants. Removal efficiency strongly affected by the chemical composition and surface properties of MP particles.	Herbort et al. 2018, Sturm et al. 2021
Bioagglomeration (bioflocculation)	50 - 80	Bioflocculants produced by microbes and jellyfish. Only bench-scale results have been reported.	Cunha et al. 2020, Li et al. 2020, Lengar et al. 2021
Retention ponds	85	Used for stormwater treatment. Research data on MP removal efficiencies is still limited.	Borg Olesen et al. 2019
Bioretention systems	70-80	For stormwater treatment	Smyth et al. 2021, Lange et al. 2021
Phytofiltration (vegetation-based accumulation)		Research data is still very limited.	Ebere et al. 2019, Masiá et al. 2020

Final disposal and treatment alternatives for MP-laden matrices created with MP removal processes

The above-reviewed studies on various technologies and methods for MPs removal from wastewater and stormwater do not include concrete treatment methods for matrices enriched with MPs. These materials include sewage sludge, pond sediments, sand, plant biomasses and membrane filtration retentates. In this section, possible options for final disposal or treatment of these materials are discussed.

Practices for the use of treated sewage sludge vary between countries. Rolsky et al. (2020) reported disposal alternatives for twelve countries (Figure 5). Use of biosolids (treated sewage sludge) in agriculture was common in Norway (82%), Ireland (63%), US (55%), China (45%), Canada (43%), Germany (38%), Sweden (36%) and Scotland (24%). Use as soil/compost for landscaping was common in Finland (89%), Scotland (40%), Sweden (27%) and Italy (26%). In the Netherlands nearly all biosolids (99%) were incinerated, which was common also in South Korea (55%), Canada (47%), and Scotland (35%). Landfilling was also used in many countries.

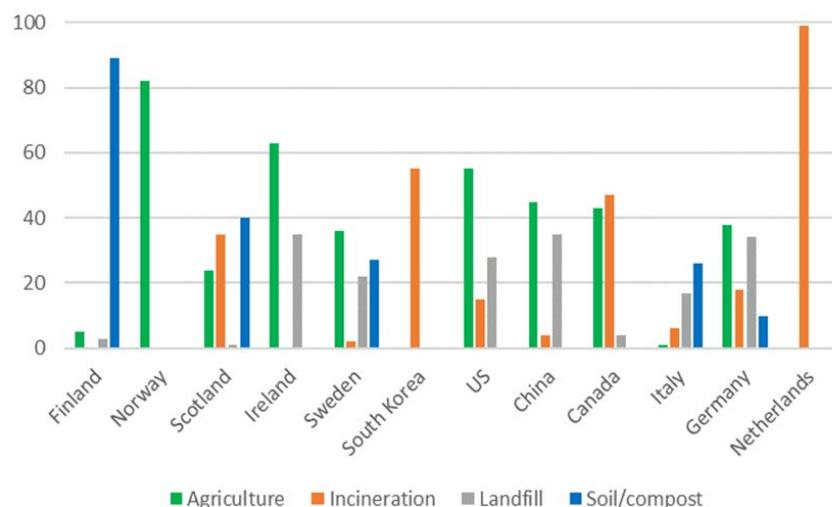


Figure 5. Reported percent of treated sewage sludge usage per country (Figure based on data from Rolsky et al. 2020).

Due to the efficient removal of MPs during wastewater treatment, MPs are present in sewage sludge in high concentrations. However, the current treatment methods for biosolids are insufficient to degrade MPs. On the other hand, it may not be required in the national legislation. When compost standards were compared within Europe, America and Australia, the most precautionary indication requires that plastics > 2 mm are < 0.5% of compost weight in dry mass (Ruggero et al. 2020). Moreover, plastic pieces which pass the 2 mm mesh are considered assimilable to compost, being the threshold in some countries 10 to 15 mm (e.g. Spain and New Zealand), while in some other European countries and USA plastic is not mentioned in the requirements for impurities inspection.

To the best of our best knowledge, incineration of sewage sludge at high temperature is the only treatment method so far which efficiently degrades MPs and pose no further risk of MPs spreading to the environment.

Most research on MPs removal is concentrating on WWTPs where the main recipient of MPs is sewage sludge. However, stormwater also contains significant amounts of MPs and various filtration methods are being developed to remove them.

MPs are either concentrated on the filter matrix, such as sand or biochar, or in the sludge cake from disc and membrane filters, depending on the filtration method used. The reviewed literature does not include the filter material regeneration or disposal. However, these final disposal methods are crucial to avoid MPs entering the environment. Incineration, anaerobic digestion, thermolysis/pyrolysis, and chemical recycling are some of the suggested final disposal methods (Zhang et al. 2021).

Key conclusions

From the analysis of existing and emerging technologies, and methods for microplastics (MPs) removal especially from urban aquatic environments contained in this policy brief, the following conclusions could be extracted:

- wastewater treatment processes need to be further optimized to retain MPs more efficiently without compromising other water treatment goals;
- current wastewater treatment technologies and methods are being replaced by novel technologies to better meet the stringent requirements for effluents, together with efficient removal of MPs. Membrane bioreactor is an example of such a technology with higher removal rates for organic pollutants and MPs than with the conventional activated sludge process;

- the removal of MPs from stormwaters usually requires solutions developed specifically for stormwater treatment. These methods should be locally adaptable, cost-efficient and with minimal need for management. So far, retention of stormwater microplastics has been the subject of only limited number of studies based on filtration or sedimentation;
- new and innovative MP removal technologies and methods suitable especially for stormwaters, including urban snow meltwaters, are needed and the MP removal efficiency of these methods demonstrated in pilot studies;
- techno-economic analysis and life cycle assessment for these emerging technologies and methods compared with existing technologies are essential to evaluate their technical and economic feasibility as well as the environmental impact of the processes under development;
- microplastics characteristics, including size, shape, and surface properties, can significantly affect the behavior of MP particles in various MP removal technologies, and therefore, determine the removal efficiency. Standardized protocols for MP sampling, sample preparation and analytical methods suitable for various MP types, e.g. tyre and road wear particles, are crucial. Further, for evaluating and comparing the MP removal technologies and their efficiencies, MPs concentrations should be based on the mass of MPs, in addition to MP particle numbers;
- investigation and development of sustainable and cost-effective methods for treatment of MP-laden matrices (sewage sludge, pond sediment, sand, plant biomass, membrane retentate) created with MP retainment processes is needed to avoid shifting MPs and their effects from one environmental compartment to another.

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