Policy brief on existing and emerging technologies for microplastics removal from wastewater and stormwater

Baltic Marine Environment Protection Commission

Policy briefs

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, wherever microplastics enter the environment all these chemical compounds should also be considered. 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 (sun)light, rain, wind, and/or by biological breakdown (Scalenghe 2018). On the other hand, according to Oberbeckmann & Labrenz (2020), microplastics in the ocean represent recalcitrant substances for microorganisms and will probably not be microbially degraded in any period of time relevant to human society. Ward et al. (2019) suggested that polystyrene may be more susceptible to degradation in the environment than previously recognized and that sunlight, rather than microbes, has the most important role in the degradation process. Additionally, Scalenghe (2018) states that thermoplastics are not easily biodegradable; especially polystyrene is, apparently, unaffected by biodegradation.

This policy brief presents existing and emerging technologies, and methods for MPs removal especially from urban aquatic environments (Vahvaselkä & Winquist 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.

Regulatory framework

At regional level, the revised HELCOM Recommendation on reduction of discharges from urban areas by the proper management of storm water systems states that "measures to ensure storm water quality should be taken already at the source to prevent the deterioration of the quality of storm water (e.g. efficient dry street cleaning and other measures minimizing microparticles associated with traffic; management of storm waters and waste on construction sites)" (HELCOM 2021). The revision process of the HELCOM Recommendation to, among other issues, address the problem of microplastics in stormwater management, is aligned with the European revision process on the matter which is currently being held in the frame of the revision of the Urban Wastewater Treatment Directive. The European Commission launched the impact assessment for the revision of the Directive by publishing its roadmap in 2020. The revision of the Directive addresses those areas of improvement that were identified in the evaluation and aligns the directive with the objectives of the European Green Deal and the Zero Pollution Action Plan. It is to point out that the evaluation of the Directive concluded that it currently does not deal adequately with new concerns, such as microplastics in the waste water system (EC 2019). A decision by the Commission on the revision of the Urban Wastewater Treatment Directive is foreseen for the second quarter of 2022 (EC 2022). It may be expected that best environmental practices (BEP) for microplastics removal from wastewater and stormwater are pointed out in the revised Directive. Finally, at national level in the Baltic Sea area, there are not currently, to our knowledge, regulatory measures on BEP for microplastics removal from wastewater and stormwater.

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, fishing gear and marine paints (Eunomia & ICF 2018). Microplastics should be addressed as close as possible to these identified sources, being the end-of-pipe solutions, linked to the improvement of the efficiency of the removal of MPs in WWTPs, the last step towards the reduction of the presence of this pollutant in the aquatic environment.

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, although removal efficiency is not 100%. In addition, since 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, Winquist 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 possibly migrate to ground water (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.

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, solid particles and nutrients 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).

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

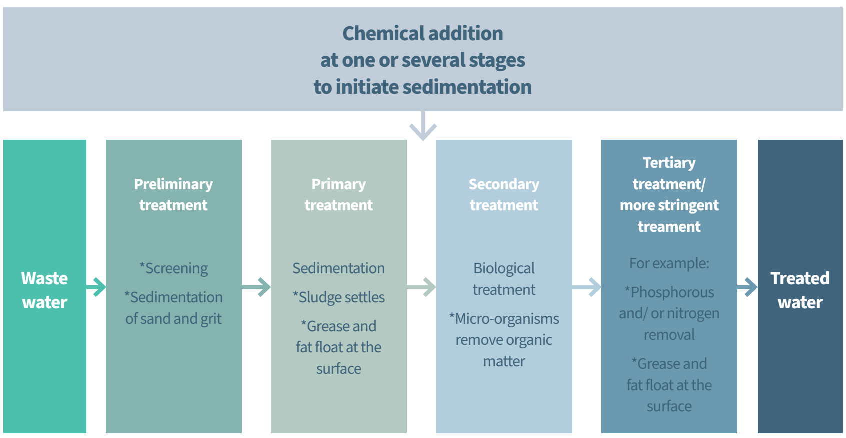


Figure 1. A general overview of treatment steps in wastewater treatment plants (Norén et al. 2016).

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).

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 at 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.

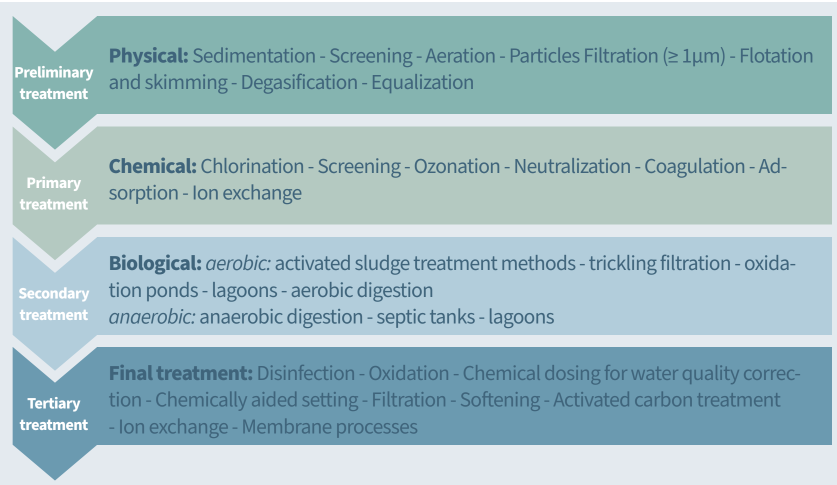


Figure 2. Classification of wastewater treatment methods (Poerio et al. 2019).

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.

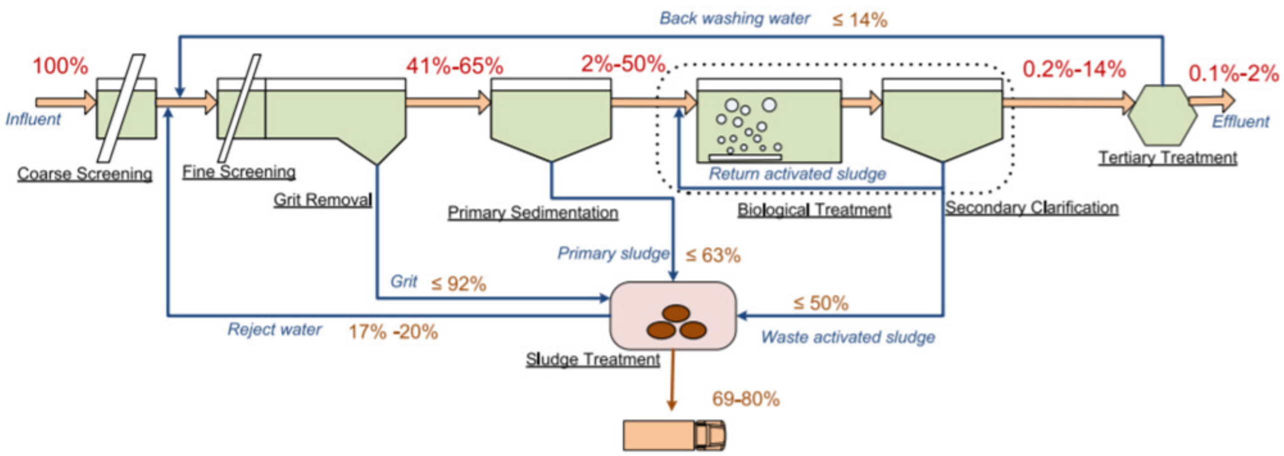


Figure 3. Estimated microplastic particle flow in wastewater treatment plants with primary, secondary and tertiary treatment processes (Sun et al. 2019).

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.

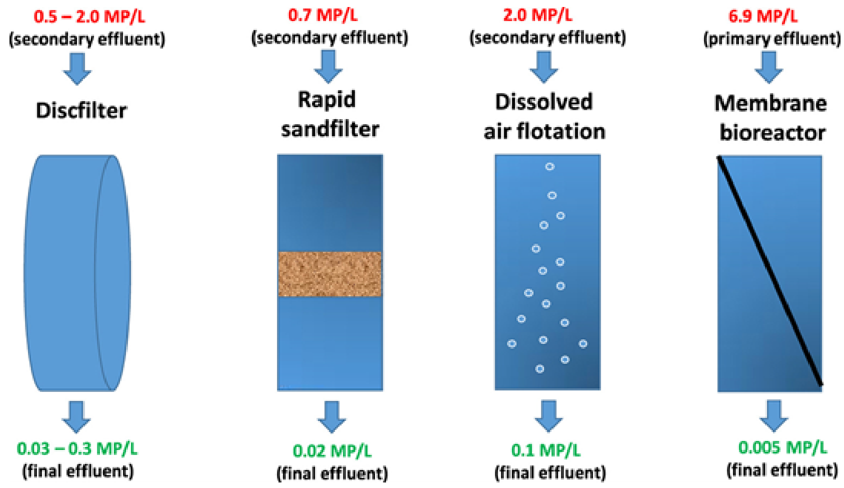


Figure 4. The efficiency of different tertiary and secondary (MBR) treatment techniques (removal rates: DF 40–98.5%, RSF 97%, DAF 95% of the microplasrics (MPs) from secondary effluent; MBR decreased 99.9% of the MPs from primary effluent providing also the lowest MP concentration in the final effluent)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

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. Membrane fouling, high energy consumption.	Talvitie et al. 2017a, Lares et al. 2018, Bayo et al. 2020, Baresel et al. 2019
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 devises, 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.	Herborg 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. (2021), 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)
Phytofiltration (vegetation-based accumulation)		Research data is still very limited.	Ebene et al. (2019), Masiá et al. (2020)

Therefore, regular street sweeping might prevent transport of these MPs via stormwater out in the environment (Järlskog 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 bioflocculants 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.

Final disposal and treatment alternatives for microplastic-laden matrices created with microplastic 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.

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 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).

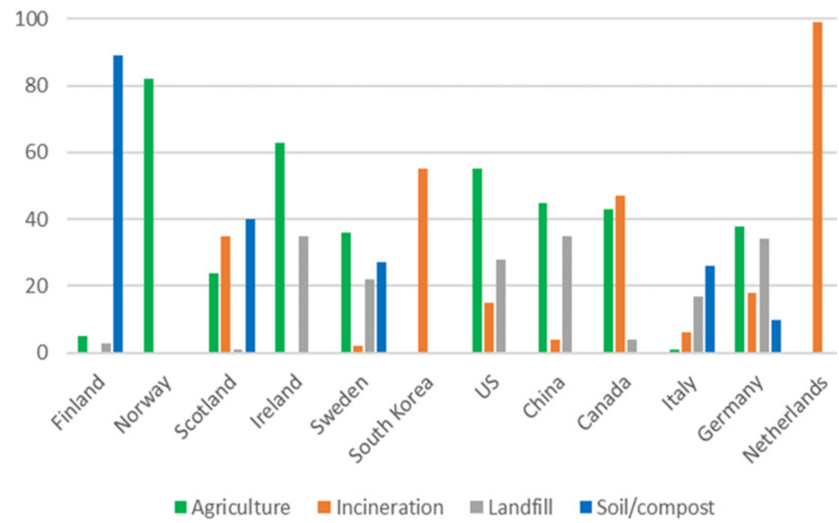
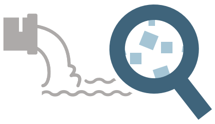


Figure 5. Reported percent of treated sewage sludge usage per country (Figure based on data from Rolsky et al. 2020).

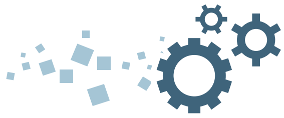
Key messages

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 messages could be extracted:

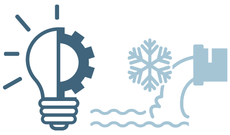


Wastewater treatment processes need to be further optimized to retain MPs more efficiently without compromising other water treatment goals.

Current wastewater treatment technologies and methods should be complemented 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.

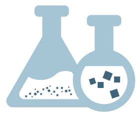


The removal of MPs from stormwaters usually requires solutions developed specifically for stormwater treatment. These methods should be locally adaptable, cost-efficient and with minimal need for management. So far, retention of stormwater microplastics has been the subject of only limited number of 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.

References

Andersson-Sköld, Y., Johannesson, M., Gustafsson, M., Järlskog, I., Lithner, D., Polukarova, M. & Strömvall, A.-M. 2020. Microplastics from tyre and road wear – A literature review. Swedish National Road and Transport Research Institute (VTI), VTI rapport 1028A. http://vti.diva-portal.org/smash/get/diva2:1430623/FULLTEXT02.pdf.

Andrady, A.L. & Neal, M.A. 2009. Applications and societal benefits of plastics. Philosophical Transactions of the Royal Society B 364: 1977-1984.

Baresel, C. & Olshammar, M. 2019. On the importance of sanitary sewer overflow on the total discharge of microplastics from sewage water. Journal of Environmental Protection 10: 1105-1118. https://doi.org/10.4236/jep.2019.109065.

Bollmann, U.E., Simon, M.,Vollertsen, J. & Bester, K. 2019. Assessment of input of organic micropollutants and microplastic into the Baltic Sea by urban waters. Marine Pollution Bulletin 148: 149–155. https://doi.org/10.1016/j.marpolbul.2019.07.014.

Borg Olesen, K., Stephansen, D.A., van Alst, N. & Vollertsen, J. 2019. Microplastics in a stormwater pond. Water 11: 1366. https://doi.org/10.3390/w11071466.

Bui, X.-T., Vo, T.-D.-H., Nguyen, P.-T., Nguyen, V.-T., Dao, T.-S. & Nguyen, P.-D. 2020. Microplastics pollution in wastewater: Characteristics, occurrence and removal technologies. Environmental Technology & Innovation 19: 101013. https://doi.org/10.1016/j.eti.2020.101013.

Ebere, E.C., Wirnkor, V.A. & Ngozi, V.E. 2019. Uptake of microplastics by plant: a reason to worry or to be happy? World Scientific News 131: 256–267. Available at http://www.worldscientificnews.com/article-in-press/2019-2/131-134-2019/.

EC 2022. Urban Waste Water Treatment Directive – Review. Available at: https://ec.europa.eu/environment/water/water-urbanwaste/evaluation/index_en.htm

EC 2019. Executive summary of the evaluation of the Council Directive 91/271/EEC of 21 May 1991, concerning urban waste-water treatment, SWD(2019) 701 final. Available at: https://ec.europa.eu/environment/water/water-urbanwaste/pdf/1_EN_dts_resume_evaluation_part1_final.pdf. Accessed 4 April 2022.

ECHA 2021. Microplastics. https://echa.europa.eu/hot-topics/microplastics. Accessed 29 July 2021.

Eunomia & ICF 2018. Investigating options for reducing releases in the aquatic environment of microplastics emitted by (but not intentionally added in) products. Final report for DG Environment of the European Commission. https://www.eunomia.co.uk/reports-tools/investigating-options-for-reducing-releases-in-the-aquatic-environment-of-microplastics-emitted-by-products/.

Gao, D., Li, X.-Y. & Liu, H.-T. 2020. Source, occurrence, migration and potential environmental risk of microplastics in sewage sludge and during sludge amendment to soil. Science of the Total Environment 742: 140355. https://doi.org/10.1016/j.scitotenv.2020.140355.

GESAMP 2016. Sources, fate and effects of microplastics in the marine environment: part two of a global assessment" (Kershaw, P.J. and Rochman, C.M., eds.). IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection. http://www.gesamp.org/publications/microplastics-in-the-marine-environment-part-2.

HELCOM 2021. HELCOM Recommendation 23/5-Rev.1 on the reduction of discharges from urban areas by the proper management of storm water systems. Available at: https://helcom.fi/wp-content/uploads/2021/06/Rec-23-5-Rev.1.pdf.

Lassen, C., Foss Hansen, S., Magnusson, K., Norén, F., Bloch Hartmann, N. I., Jensen, P. R., Nielsen, T.G. & Brinch, A. 2015. Microplastics – Occurrence, effects and sources of releases to the environment in Denmark, Environmental project No. 1793. The Danish Environ-mental Protection Agency. https://www2.mst.dk/Udgiv/publications/2015/10/978-87-93352-80-3.pdf.

Li, L., Luo, Y.,Li, R., Zhou, Q., Peijnenburg, W.J.G.M., Yin, N., Yang, J., Tu, C. & Zhang, Y. 2020. Effective uptake of submicrometre plastics by crop plants via a crack-entry mode. Nature Sustainability 3: 929–937. https://doi.org/10.1038/s41893-020-0567-9.

Liu, F., Borg Olesen, K., Reimer Borregaard, A. & Vollertsen, J. 2019a. Microplastics in urban and highway stormwater retention ponds. Science of the Total Environment 671: 992-1000. https://doi.org/10.1016/j.scitotenv.2019.03.416.

Norén, K., Magnusson, K., Westling, K., Olshammar, M. 2016. Report concerning techniques to reduce litter in waste water and storm water. SMED Report No 193 2016, 73 p. http://www.smed.se/vatten/3960.

Oberbeckmann, S. & Labrenz, M. 2020. Marine Microbial Assemblages on Microplastics: Diversity, Adaptation, and Role in Degradation. Ann Rev Mar Sci. 12: 209-232. doi: 10.1146/annurev-marine-010419-010633. Epub 2019 Jun 21. PMID: 31226027.

Padervend, M., Lichtfouse, E., Robert, D. & Wang, C. 2020. Removal of microplastics from the environment. A review. Environmental Chemistry Letters 18: 807-828. https://doi.org/10.1007/s10311-020-00983-1.

Pankkonen, P. 2020. Urban stormwater microplastics – Characteristics and removal using a developed filtration system. Master's thesis. Water and Environmental Engineering, Aalto University. 46 p. http://urn.fi/URN:NBN:fi:aalto-202005243251.

Poerio, T., Piacentini, E., Mazzei, R. 2019. Membrane processes for microplastic removal. Molecules 24: 4148. https://doi.org/10.3390/molecules24224148.

Rajala, K., Grönfors, O., Hesampour, M. &Mikola, A. 2020. Removal of microplastics from secondary wastewater treatment plant effluent by coagulation/flocculation with iron, aluminium and polyamine-based chemicals. Water Research 183: 116045. https://doi.org/10.1016/j.watres.2020.116045.

Rolsky, G., Kelkar, V., Driver, E. ,Halden, R.U. 2020. Municipal sewage sludge as a source of microplastics in the environment. Current Opinion in Environmental Science & Health 14: 16–22. https://doi.org/10.1016/j.coesh.2019.12.001.

Scalenghe, R. 2018. Resource or waste? A perspective of plastics degradation in soil with a focus on end-of-life options. Heliyon 4: e00941. https://doi.org/10.1016/j.heliyon.2018.e00941.

Shahi, N.K., Maeng, M., Kima, D. & Dockko, S. 2020. Removal behavior of microplastics using alum coagulant and its enhancement using polyamine-coated sand. Process Safety and Environmental Protection 141: 9-17. https://doi.org/10.1016/j.psep.2020.05.020.

Simon, M., van Alst, N. & Vollertsen, J. 2018. Quantification of microplastic mass and removal rates at wastewater treatment plants applying Focal Plane Array (FPA)-based Fourier Transform Infrared (FT-IR) imaging. Water Research 142: 1-9. https://doi.org/10.1016/j.watres.2018.05.019.

Simon, M., Vianello, A. &Vollertsen, J. 2019. Removal of >10 µm microplastic particles from treated wastewater by a disc filter. Water 11: 1935. https://doi.org/10.3390/w11091935.

Sun, J., Dai, X., Wang, Q., van Loosdrecht, M.C.M. & Ni, B.-J. 2019. Microplastics in wastewater treatment plants: Detection, occurrence and removal. Water Research 152: 21-37. https://doi.org/10.1016/j.watres.2018.12.050.

Talvitie, J., Mikola, A., Koistinen, A. & Setälä, O. 2017a. Solutions to microplastic pollution - Removal of microplastics from wastewater effluent with advanced wastewater treatment technologies. Water Research 123: 401 – 407. https://doi.org/10.1016/j.watres.2017.07.005.

Talvitie, J., Mikola, A., Setälä, O., Heinonen, M. & Koistinen, A. 2017b. How well is microlitter purified from wastewater? - A detailed study on the stepwise removal of microlitter in a tertiary level wastewater treatment plant. Water Research 109: 164 – 172. https://doi.org/10.1016/j.watres.2016.11.046.

Vahvaselkä, M. & Winquist, E. 2021. Existing and emerging technologies for microplastics removal : Review report of the FanpLESStic-sea project. Natural resources and bioeconomy studies xx/2021. Natural Resources Institute Finland. Helsinki. 35 p.

Vogelsang, C., Lusher, A. L., Dadkhah, M. E., Sundvor, I., Umar, M., Ranneklev, S. B., Eidsvoll, D. & Meland, S. 2020. Microplastics in road dust – characteristics, pathways and measures. Norwegian Environment Agency (Miljødirektoratet). Norwegian Institute for Water Research (NIVA). https://www.miljodirektoratet.no/globalassets/publikasjoner/M959/M959.pdf.

Wang, Z., Lin, T. & Chen, W. 2020. Occurrence and removal of microplastics in an advanced drinking water treatment plant (ADWTP). Science of the Total Environment 700: 134520. https://doi.org/10.1016/j.scitotenv.2019.134520.

Ward, C.P., Armstrong, C.J., Walsh, A.N., Jackson, J.H. & Reddy, C.M. 2019. Sunlight converts polystyrene to carbon dioxide and dissolved organic carbon. Environmental Science and Technology Letters 6: 669–674. https://pubs.acs.org/doi/abs/10.1021/acs.est-lett.9b00532.

Ward, C.P. & Reddy, C.M. 2020. We need better data about the environmental persistence of plastic goods. Proceedings of the National Academy of Sciences of the United States of America 117: 14618–14621. www.pnas.org/cgi/doi/10.1073/pnas.2008009117.

Winquist, E., Vahvaselkä, M., Vuola, M. & Sainio, P. 2021. Traffic microplastics – solutions to mitigate the problem: FanpLESStic-sea project report. Natural resources and bioeconomy studies 56/2021. Natural Resources Institute Finland. Helsinki. 23 p. http://urn.fi/URN:ISBN:978-952-380-255-1.

Zhang, Y., Jiang, H., Bian, K., Wang, H. & Wang, C.2021 A critical review of control and removal strategies for microplastics from aquatic environments. Journal of Environmental Chemical Engineering 9: 105463. https://doi.org/10.1016/j.jece.2021.105463.