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Review report of the FanpLESStic-sea project

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Summary

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In this review, existing and emerging technologies and methods for removal of microplastics (MPs) especially from urban aquatic environments are presented. In recent years, several physical, chemical and biological technologies and methods for MP removal have been investigated and developed mainly for wastewaters. 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. MP removal efficiencies higher than 90% have been reported for several technologies and methods. Potential methods based on activities of microorganisms, higher marine organisms and plants are also discussed.

In general, MP particles are efficiently removed from wastewaters during wastewater treatment. However, as wastewater treatment plants receive vast amounts of MP-containing wastewaters, these treatment processes are in the need for further optimization to retain MPs even more efficiently. On the other hand, present wastewater treatment technologies and methods can be replaced with novel technologies to better meet the stringent requirements for treated waters, 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 in conventional activated sludge process.

In addition to wastewaters, also stormwaters contain significant amounts of MPs. However, most stormwaters end up in aquatic environments either untreated or only partially purified. The solutions for removal of MPs from stormwaters should be locally adaptable, cost-efficient and with minimal need for management. Recently, removal of stormwater MPs has been the subject of studies focusing on sedimentation ponds, filtration and bioretention systems. New and innovative MP removal technologies and methods suitable especially for stormwaters including urban snow meltwaters are still needed and the MP removal efficiency of these methods should be demonstrated in pilot studies.

Finally, treatment methods of MP-laden matrices (e.g. sewage sludge, pond sediments, sand, plant biomass, membrane retentate) created with MP retainment processes are lacking. Therefore, research and development of sustainable and cost-effective methods are urgently needed to avoid mere shifting of MPs and their effects from one environmental compartment to another.

Keywords: Microplastics, removal, technology, method, wastewater, stormwater, snow

Contents

List of abbreviations

CAS	conventional activated sludge
DM	dynamic membrane
DW	dry weight
EC	electrocoagulation
EPS	extracellular polymeric substance
LCA	life cycle assessment
MBR	membrane bioreactor
MF	microfiltration
MP	microplastic
PA	polyamide
PE	polyethylene
PES	polyester
PET	polyethylene terephthalate
POP	persistent organic pollutant
PP	polypropylene
PS	polystyrene
PU	polyurethane
PVC	polyvinyl chloride
UF	ultrafiltration
WWTP	wastewater treatment plant

1. Introduction

Microplastics (MPs), polymer particles less than 5 mm in size, are often categorized as primary MPs that are purposely manufactured in microscopic size to carry out a specific function, and secondary MPs representing the results of wear and tear or fragmentation of larger plastic items (GESAMP 2016). The largest share of MP pollution originates from the secondary sources (Lassen et al. 2015). The share of primary sources is most likely to decrease even more in the European Union since the European Commission and EU member states are currently considering a restriction for intentionally added MPs in products at the EU level (ECHA 2021). However, the pollution from secondary sources remains and is being approached both with preventive and removal methods.

Estimated sources of secondary MPs are traffic (tyre and break wear particles, road markings), building paints, clothing, artificial turf, fishing gear and marine paints (Figure 1). Substantial amounts of MPs are transported into and retained in wastewater treatment plants (WWTPs). In separate sewer systems instead of combined sewers, stormwater runoffs are separated from the wastewater sewer system, thus preventing wastewater sewer overflows to the environment during heavy rains. Then, however, especially traffic related MPs in stormwaters end up in surface waters and soil even without any treatment (Bollmann et al. 2019, Baresel & Olshammar 2019, Pankkonen 2020, Winquist et al. 2021). Moreover, also sewage sludge is a source of MPs, since 69–99% of MPs in wastewater is transferred to sewage sludge during wastewater treatment (Sun et al. 2019).

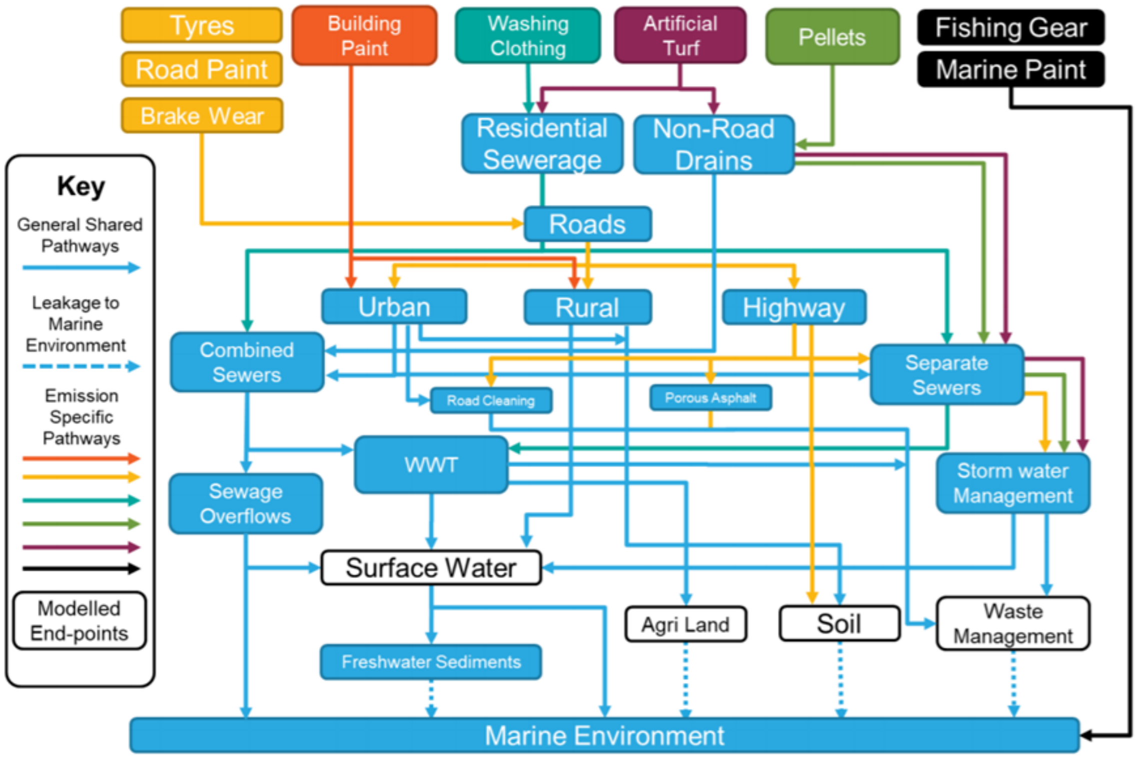

Figure 1. Estimated sources and emission pathways of microplastics (Eunomia & ICF 2018).

MPs as well as macroplastics are very persistent in the environment, except those plastics designed to be biodegradable. Rather than degrading, MPs are further fragmenting to smaller nanoplastics in the environment. The characteristics and toxicity of MPs is dependent on their chemical composition. MPs are rarely composed of just one individual polymer, but instead are mixed with additives such as carbon or silica to give strength, thermal stabilizers, plasticizers, fire retardants, UV stabilizers, colorants etc. (Scalenghe 2018). Especially certain additives such as plasticizers (phthalates, bisphenol A) and flame retardants (polybrominated diphenyl ethers) are well known as endocrine disrupting compounds (Sun et al. 2019). In addition to containing hazardous substances themselves, MPs are effective in adsorbing persistent organic pollutants (POPs) due to their large surface area to volume ratio and hydrophobic nature of the surface. The concentrations of organic contaminants can be one million times higher on the surfaces of MPs compared to the surrounding environment (Sun et al. 2019).

There is currently insufficient knowledge to evaluate the effects of MPs for the environment and human health. First, the research on the occurrence of the MPs in the environment has started only recently and standardized analysis methods are still lacking which makes the comparison of the results very difficult (Simon et al. 2018, Borg Olesen et al. 2019). Moreover, the effects of MPs have been studied so far mainly with certain marine species and the information of micro/nanoplastic enrichment in the food-chain is limited (Setälä et al. 2014, Näkki 2021). Despite this, the facts that MP particles are persistent in the environment, they contain hazardous substances as additives, and adsorb organic contaminants on their surfaces, are convincing enough to develop restrictions to their release in the environment, as well as effective removal methods (Andersson-Sköld et al. 2020).

This review report is an output of the FanpLESStic-sea – "Initiatives to remove microplastics before they enter the sea" project (2019–2021), which is an EU Interreg funded Baltic Sea Region project aimed at decreasing and removing MPs in the Baltic Sea. The report is part of the Activity 3.1 State-of-the-art microplastic removal technologies lead by the Natural Resources Institute Finland (Luke), which aims to develop technologies for MP removal from wastewater, stormwaters and meltwaters of urban snow to prevent the MPs from entering the receiving water bodies.

The previous report of FanpLESStic-sea project focused on preventive methods to mitigate traffic MPs, which are the largest group of MPs in stormwaters (Winquist et al. 2021). The aim of the present review is to offer an overview on MP removal technologies especially from urban aquatic environments. The main body of scientific MP removal literature concentrates on MP levels and total removal rates in WWTPs and at individual treatment stages. For this review, also emerging and innovative methods, especially technologies suitable for removing MPs from stormwaters, e.g. road runoff, and from meltwaters of urban snow, were searched and described. Finally, treatment options for various MP containing matrices, including sewage sludge, originating from the use of removal technologies are discussed. In chapters 5–8, various technologies and methods used or tested for MP removal from wastewater and stormwater are presented.

It should be emphasized that the comparison of literature data on MPs concentrations and removal efficiencies by various technologies can be problematic. The main reason is that different analytical approaches have been used for quantification of MPs, that also sampling methods differ, and that the lower size limit of detection and quantification varies between studies. Also, most studies report MPs in terms of particle numbers per unit volume, which makes it difficult to compare the results as MP particles break up and fragment over time. Therefore, this measure is insufficient when assessing the efficiency of treatment methods. There, the mass of MPs, as a conserved quantity, should be used (Simon et al. 2018, Borg Olesen et al. 2019, Poerio et al. 2019). The MP concentrations in this review are presented in units reported in the original studies, mainly as MP particle numbers per volume.

2. Fate of microplastics in the environment

Microplastics in the environment are composed of the originating plastic polymers and the eventual additives. In addition, other compounds, such as POPs may have been adsorbed on the surfaces of the particles. Thus, their fate in the environment should be considered in the view of these chemical compounds. Overall, plastic polymers are known to be very persistent in the environment. Some estimates about the reported environmental lifetimes of different (nonbiodegradable) plastics are given in Figure 2. However, what makes this issue complicated is that plastics have been produced only for about sixty years and no one really knows how long they will last in the environment (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) suggested 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. They showed in their study that PS was completely photochemically oxidized to carbon dioxide and partially photochemically oxidized to dissolved organic carbon. Moreover, lifetimes of complete and partial photochemical oxidation were estimated to occur on centennial and decadal time scales, respectively, which also challenge the prevailing assumption that polystyrene persists in the environment for millennia (Figure 2).

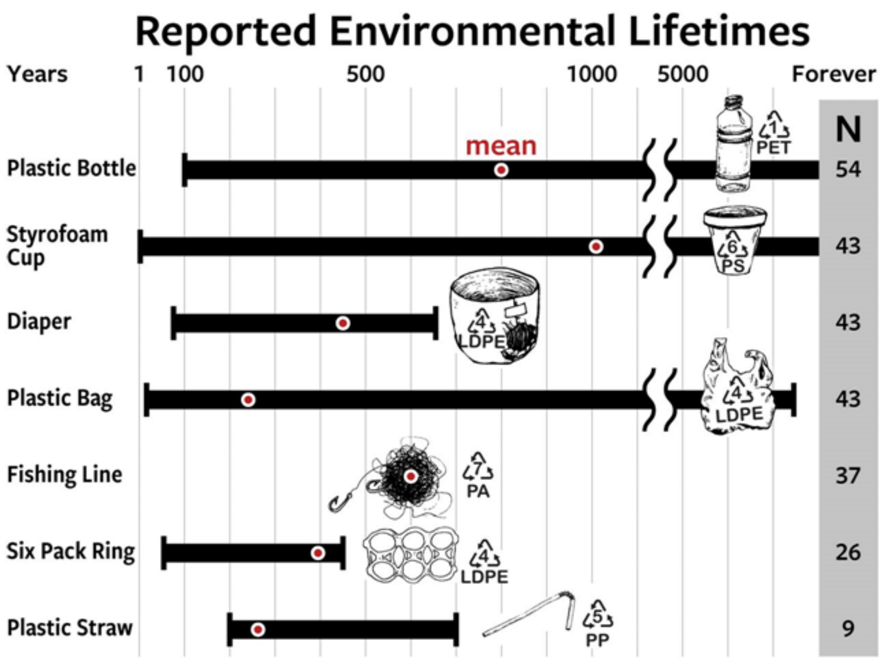

Figure 2. Review of 57 information graphics and documents that report environmental lifetimes of common plastic consumer goods. The bars represent the range of estimates, the red circles represent the mean of estimates, and the number of estimates for each plastic good (N) is provided on the right (N = 255 in total). The recycling number corresponds to the base polymer of each good. PET = polyethylene terephthalate, PS = polystyrene, LDPE = low-density polyethylene, PA = polyamide, and PP = polypropylene. (Ward & Reddy 2020, image credit: Natalie Reiner).

Plastic polymers in soil are less exposed to sunlight, but experimental data show biodegradation of plastics in soils at least to some extent by certain bacteria and several fungal species, e.g. *Aspergillus* sp., *Penicillium* sp. and *Fusarium* sp. (Wu et al. 2017, Scalenghe 2018). By screening natural microbial communities from a PET bottle recycling site, Yoshida et al. (2016) were able to isolate a novel bacterium, *Ideonella sakaiensis* 201-F6, which degrades PET and uses it as major energy and carbon source. Once identified, microorganisms with the enzymatic machinery needed to degrade plastic polymers could serve as an environmental remediation strategy. However, except for these few examples, the bioremediation of macroplastics or MPs is not yet possible to the best of our knowledge.

3. Wastewater treatment processes and microplastics removal

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 3. 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).

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 the 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. According to recent studies, the concentrations of MPs in the influents and effluents of WWTPs are in the range of 1–18 000 and 1–450 MP particles/L, respectively (Talvitie et al. 2017b, Simon et al. 2018, Sun et al. 2019). In general, the WWTPs with tertiary treatment processes yield a lower MP concentration in the effluent than those with primary or secondary treatment processes only. 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).

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).

The MP types detected in WWTPs include more than 30 kinds of MP polymers, most abundant polymers found in influents and effluents of WWTPs being polyethylene (PE), polyester (PES), polyamide (PA) and polyethylene terephthalate (PET). Polypropylene (PP), polystyrene (PS) and polyurethane (PU) have also been commonly detected. Particle size distribution and particle shapes of the MPs have also been documented (Sun et al. 2019, Simon et al. 2018, Talvitie et al. 2017b, Zhang et al. 2020, Rasmussen et al. 2021).

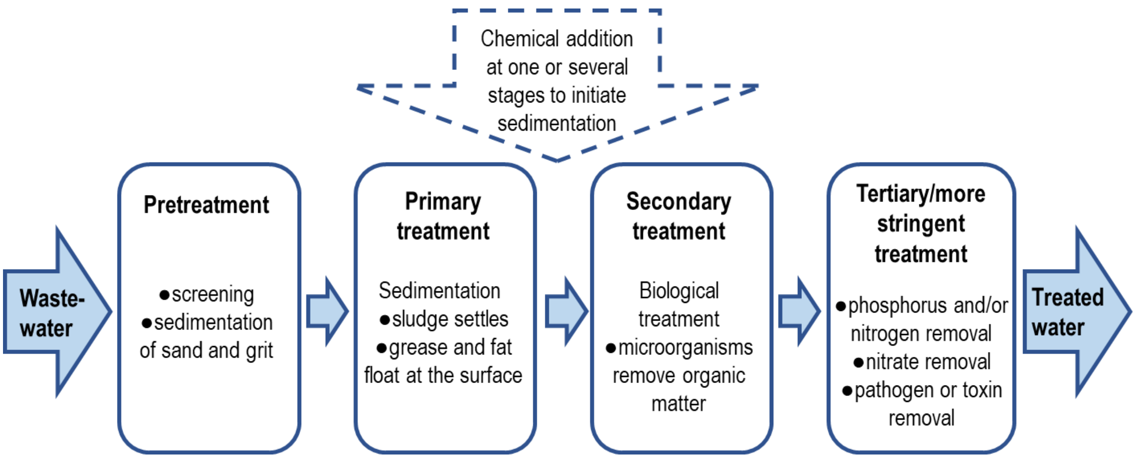

Figure 3. A general overview of treatment steps in wastewater treatment plants (modified from Norén et al. 2016).

The MP removal efficiencies at different steps of wastewater treatment processes have also been investigated (Talvitie et al. 2017b, Lares et al. 2018). Already after primary treatment, approximately 50–98% of MP particles were removed (Figure 4), especially those of larger size. During secondary treatment, the MP level in the wastewater decreased to 0.2–14%. The tertiary treatment may provide additional MP removal. Then, the MP level in the effluent decreased to 0.2–2% compared to the influent and the smallest size fractions (20–190 µm) were the most abundant (Sun et al. 2019). The relative abundance of MP fiber particles compared to MP fragments in effluents is reported to be higher than in the influent.

It is evident from studies on the transport and fate of MPs in WWTPs that most of the MP particles present in influent wastewater are retained in the sewage sludge. Reported MP concentrations in sewage sludge range from 1 to 240 particles per gram of dry sludge (Lares et al. 2018, Sun et al. 2019, Edo et al. 2020). The fate of MPs in sewage sludge is discussed in Chapter 9.

The estimated MP discharges from a secondary WWTP varies between 10^6–10^8 particles/day (Talvitie et al. 2017b, Mintenig et al. 2017, Murphy et al. 2016, Edo et al. 2020). Given the large volumes of WWTP effluents discharged to the aquatic environment, secondary and even tertiary level WWTPs may constitute a considerable source of MP pollution (Talvitie et al. 2017b, Edo et al. 2020; Simon et al. 2018). Simon et al. (2018) estimated total MP discharge of all Danish WWTPs to be slightly more than 3 tons/year. From all WWTPs in the Baltic Sea basin, a total MP discharge of 2–90 tons/year was calculated by Baresel & Ohlshammar (2019). Further, combined sewer overflows result in MP discharges that can be in the same magnitude as from treated wastewater (Baresel & Olshammar 2019, Bollmann et al. 2019).

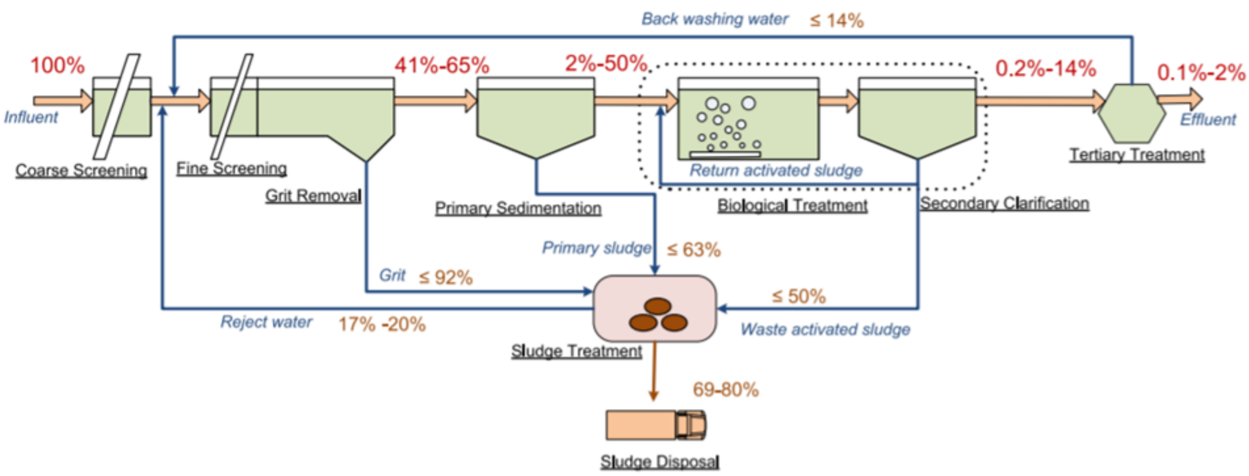

Figure 4. Estimated microplastic particle flow in wastewater treatment plants with primary, secondary and tertiary treatment processes (Sun et al. 2019).

4. Microplastics in stormwaters

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, Pankkonen 2020, Andersson-Sköld et al. 2020, Vogelsang et al. 2020).

Large variations in the amounts of MPs in urban stormwater runoffs have been documented, the concentrations being in the range of <1–6000 MP particles/L. Most of the measured MPs in stormwaters has been found in the smallest size range studied (Pankkonen 2020, Järlskog et al. 2020, Smyth et al. 2021, Lange et al. 2021). According to Smyth et al. (2021) and Lange et al. (2021), rainfall intensity was positively correlated with the MP concentrations in runoffs. Data on the efficiency of various stormwater management methods for removal of MP particles is still limited (Monira et al. 2021). In recent years, the fate of urban and highway stormwater MPs in sedimentation ponds, (bio)filters and bioretention systems has been studied (Borg Olesen et al. 2019, Pankkonen et al. 2020, Kuoppamäki et al. 2020, Smyth et al. 2021, Lange et al. 2021, Monira et al. 2021).

The abundance of MPs in the water phase and sediments of seven Danish stormwater retention ponds was recently investigated (Liu et al. 2019a, 2019b), the stormwater runoffs being from urban and highway areas. The stormwater of the ponds contained 0.5–23 MP particles/L, corresponding to an estimated 0.09–1.1 µg/L. The dominating polymers were PP, PVC, PES, PE and PS. Therefore, urban and highway stormwater runoffs could be considered as direct pathways for land based solid particles including MPs and other traffic-borne particles into freshwaters (Liu et al. 2019a). The MP concentrations in the sediments of the seven retention ponds were 1.5–130 MP particles/g dry weight (DW), corresponding to 0.12–29 µg/g DW. This shows that sediments in stormwater retention ponds can trap some of the MPs and prevent them from being transported downstream. Sedimentation and deposition are likely the main removal mechanisms. For these processes, the size, shape, and density of particles are critical parameters, as they directly affect the particle movement in water and determine their final deposition. Especially small particles (10–250 µm) were prevalent in these sediments (Liu et al. 2019b).

Borg Olesen et al. (2019) quantified the distribution of MPs in a Danish stormwater retention pond and estimated the potential of retention ponds as MP sinks. MPs were measured in the water phase, sediments and vertebrate fauna, three-spined sticklebacks and young newts. The highest MP concentrations were found in the sediments (950 particles/g DW, corresponding to 400 µg/g DW), followed by the fauna (340 particles/g DW, 13 µg/g DW) and the water (270 particles/L, 4.2 µg/L). The MP retainment efficiency of the pond 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).

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 (Järlskog et al. 2020, Fältström & Anderberg 2020, Monira et al. 2021).

5. Filtration technologies

Filtration is a common method for the removal of solid particles during water treatment. Filtration methods can be divided into granular filtration and membrane filtration according to filters (Zhang et al. 2021, Poerio et al. 2019). Various filtration-based technologies already utilized in wastewater treatment have been investigated for MP removal. These methods include sand and disc filters, biofilters, membrane bioreactors, and ultrafiltration (Talvitie et al. 2017a, Sun et al. 2019, Bui et al. 2020).

5.1. Rapid sand filters

In sand filtration, the effluent from secondary wastewater treatment is filtered through several layers with different grain sizes and materials as a final polishing step. In addition to physical separation removing suspended solids, MP particles are also adhered to the surface of the sand grains (Norén et al. 2016, Talvitie et al. 2017a).

Rapid gravity sand filters have been studied for MP removal in wastewater treatment processing with MP removal efficiencies ranging from 74 to 97%. Rapid sand filters as full-scale tertiary wastewater treatment in Finland removed 97.1% of the MPs from secondary effluent (Talvitie et al. 2017a). During the final unit operation of a WWTP in South Korea, coagulation followed by rapid sand filtration, 73.8% of MPs were removed (Hidayaturrahman & Lee 2019). Further, a MP removal rate of 75.5% by three rapid gravity sand filters in a full-scale WWTP in Spain was reported by Bayo et al. (2020).

Only limited number of publications on MPs in urban stormwater runoff and the management methods for their removal has so far been published. 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 from 0.8 to 1.2 mm) or biochar (grain size from 5 to 50 mm) was used to filtrate stormwater during three rain events. The results indicated that sand filtration removed up to 96% of MPs from stormwater runoff while the value for biochar filtration was 93%.

5.2. Disc filters

Disc filters are used commonly at WWTPs as a final polishing step for removing particles and associated pollutants from biologically treated wastewater. A disc filter process consists of a tank containing several rounded discs made of cloth material filters. Common filter sizes for polishing of effluent water are 10–40 µm. The particle removal is based on physical retention in filters and sludge cake formation inside the filter panels (Norén et al. 2016, Simon et al. 2019, Talvitie et al. 2017a).

A pilot scale disc filter examined by Talvitie et al. (2017a) for MP removal consisted of two discs composing each of 24 filter panels. Iron-based coagulant and cationic polymer were also used to enhance the particle recovery. MP removal rate with pore size 10 µm was 40.0% and with pore size 20 µm 98.5% from secondary effluent. The results should, however, be handled with care, as the variations between the replicates were high in both cases due to the disturbances in the earlier treatment stages in the WWTP (Talvitie et al. 2017a).

The disc filter used by Simon et al. (2019) for final treatment of wastewater consisted of 13 discs. Each disc had a polyester mesh of 18 µm pore size. The disc filter retained 89.7% of MP particles and 75.6% of their mass. According to the authors, the results suggest that the filter's operation was somewhat compromised and some MP particles probably either bypassed or passed through the disc filter. In a study by Hidayaturrahman & Lee (2019), membrane disc filters were tested in an industrial-scale WWTP as the final unit operation. Then, inorganic coagulant followed by membrane disc-filter resulted in a MP removal rate of 79.4%.

As a disadvantage of membrane disc filters, Bui et al. (2020) mentioned membrane fouling. Also, high-pressure backwashing process may cause the MPs to pass through the membrane.

5.3. Biofilters and bioretention systems

A pilot-scale biofilter designed to remove pharmaceuticals, personal care products and other organic micropollutants from WWTP effluents was studied by Liu et al. (2020) to evaluate its performance for MP removal. The biofilters consisted of top to bottom of a drainage layer of approximately 1.1 m of stone wool, 40 cm of Filtralite®, and 10 cm of granite gravel. The three different materials were separated by a layer of glass fiber mat. The MP removal efficiency of the biofilter was 78.5% for particle number and 88.9% for particle mass from the secondary WWTP effluent used. Most of the MP retention happened in the top filtration layer of the biofilter and MP particles of larger size and higher mass were more efficiently retained. It was expected that physical retainment was the removal mechanism of MPs since plastic biodegradation could be neglected within the hydraulic retention time of the system (Liu et al. 2020).

Nature-based designs, such as various biofilter materials and structures are increasingly investigated for stormwater management. In a laboratory-scale experiment by Kuoppamäki et al. (2021), the ability of biofilters to remove nutrients, metals and suspended solids originating from urban roadside snowmelt was studied. The fate of fluorescent PE beads up to 10 µm in diameter was also followed in the biofilters. The materials tested in biofilters were various crushed clay aggregates, crushed concrete, and filter sand. Above these materials, a layer of peat and sand mixture was added to support the growth of reed canary grass. Phosphorus and metals associated with suspended solids in the stormwater were substantially retained by all biofilters, sand being the best filtering material for removing these contaminants. MP beads were shown to accumulate along the grass root channels. No MPs were found in biofilter effluents, indicating efficient MP capturing in these biofilters (Kuoppamäki et al. 2021).

Bioretention systems for stormwater management consist of depressions filled with porous media (sand, silt and clay) covered with mulch and vegetation. The retainment of stormwater suspended solids in bioretention cells most likely occurs by physical filtration (Smyth et al. 2021). The efficiency of a bioretention cell in MP removal from parking lot runoff has recently been studied. In a two-year study period in Vaughan, Canada, an 84% decrease in the median MP concentration in the 100–5000 µm range was reported (Smyth et al. 2021).

In Sundsvall, Sweden, a highway runoff treatment system consisting of a gross pollutant trap connected either to a vertical flow vegetated bioretention cell or a non-vegetated sand filter cell was investigated during nine rain events (Lange et al. 2021). Both the vegetated and non-vegetated filter cells showed MP removal efficiencies exceeding 70% in the particle size range of 100–300 µm. For rubber and bitumen particles, the vegetated and non-vegetated filter cells did not differ in terms of MP removal efficiency, but for other MP particles the results demonstrated higher removal rates in the vegetated filter compared with the sand filter. The gross pollutant trap did not reduce rubber, bitumen of other MP particle concentrations (Lange et al. 2021).

5.4. Membrane bioreactors

In membrane bioreactors (MBR), a membrane process, e.g. microfiltration (MF) or ultrafiltration (UF), is combined with a biological process taking place in a suspended growth bioreactor (Figure 5). Therefore, a MBR process is essentially a version of the conventional activated sludge (CAS) process where a secondary clarifier or settlement tank for solid/liquid separation is replaced with a membrane (Poerio et al. 2019, Talvitie et al. 2017a, Lares et al. 2018).

Two MBR configurations exist: internal/submerged, where the membranes are immersed in and integral to the biological reactor; and external/sidestream, where membranes are a separate unit process requiring an intermediate pumping step (MBR site 2021). In a submerged MBR, the aeration system fulfils two functions, the supply of oxygen to the microorganisms that degrade the organic compounds and the cleaning of the membranes.

MBR is increasingly used for both municipal and industrial wastewater treatment. Main highlights of the MBR technology over CAS include better effluent quality, disinfection capabilities due to the membrane pore size, higher volumetric loading, reduced footprint, complete separation of hydraulic retention time and solids retention time, and process flexibility towards influent changes (Baresel et al. 2019, Xiao et al. 2019). The treatment of micropollutants, e.g. pharmaceutical residues and MPs, may also be more efficient using MBRs compared to traditional treatment systems (Baresel et al. 2019). This is partly explained by the fact that these pollutants attached to particles can efficiently be removed by filtration.

MBR technology has recently been examined for MP removal in wastewater treatment (Talvitie et al. 2017a, Lares et al. 2018, Baresel et al. 2019, Bayo et al. 2020) demonstrating high MP removal efficiencies. Talvitie et al. (2017a) used a submerged MBR pilot with 20 flat-sheet UF membrane cartridges (pore size 0.4 µm). The MBR treatment removed 99.9% of MPs from primary clarified wastewater resulting in a very low MP concentration of 0.005 MP particles/L in the final effluent.

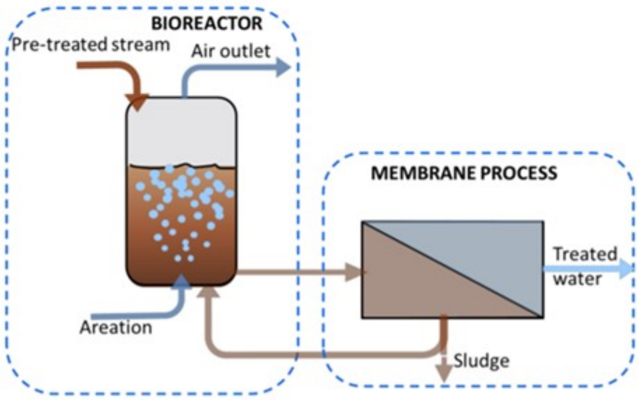

Figure 5. Schematic representation of a membrane bioreactor (MBR) process (Poerio et al. 2019). In a submerged MBR, the membranes are immersed in the bioreactor.

To reveal the temporal variation in MP levels in wastewater, conventional CAS process and MBR technology were studied for three months by Lares et al. (2018) in a WWTP. The pilot-scale MBR consisted of an anaerobic tank, an aerobic tank and a membrane filtration tank with a submerged MBR unit. Pore size of the flat-sheet membranes was 0.4 µm (Gurung et al. 2016). According to the results, MBR technology was slightly more efficient (99.4%) in removing MPs from wastewater compared to the overall CAS-based process (98.3%).

A full-scale double flow WWTP treating both domestic and industrial wastewater with a MBR system consisting of an anoxic tank, a bioreactor and a membrane filtration tank with a submerged MBR unit was examined by Bayo et al. (2020). Pore size of the flatsheet membranes was not given. The removal rate for MPs was 79.1%, lower than in the two above-reviewed studies. According to the authors, part of the MP fibres in wastewater bypassed MBR, partly due to the high pressure applied in the system.

Baresel et al. 2019 examined a pilot-scale wastewater treatment line based on MBR, including UF with membrane pore size of 0.2 µm, followed by a biofilter using granulated activated carbon as filter material. The removal capacity of the system for a broad range of micropollutants, such as pharmaceutical residues, phenolic compounds, bacteria, and MP particles present in wastewater was investigated. The results showed that the treatment system was able to remove all studied micropollutants to below detection limits or very low concentrations. No MP particles were detected in the MBR effluent (removal efficiency 100%), whereas for a full-scale CAS process including a final sand filtration treating the same wastewater had a removal efficiency of 90.7%.

One of the major drawbacks of MBR technology has been membrane fouling resulting in high energy consumption and maintenance costs. However, in recent years, a significant cost reduction of membranes, and process development decreasing energy requirements have taken place (Baresel et al. 2019, Xiao et al. 2019). Also, the performance of MBR seems not to be affected by the size, shape, and composition of MPs (Talvitie et al. 2017a, Bui et al. 2020). In conclusion, MBR is a highly promising technology for effective MP removal from wastewater. However, the factors affecting MP removal efficiencies of the MBR processes still need to be addressed in further studies (Bui et al. 2020).

5.5. Dynamic membranes

Dynamic membranes (DM) are a promising technology for the removal of low-density, non-degradable microparticles, such as plastics, due to its low cost, easy cleaning, and low energy consumption (Li et al. 2018, Zhang et al. 2021). This technology is based on the formation of a cake layer, which acts as a secondary membrane created when particles and other foulants in the wastewater are filtered through a supporting membrane. Since the filtration mechanism of the DM is quite different compared to the MF/UF processes, in the sense that the fouling and foulants are necessary to create the DM layer, the resistance to filtration is caused exclusively by the layer of the cake. However, thicker layers and dense fouling cause a loss of membrane performance. The parameters that must be taken into consideration to limit the formation of fouling are the same that are involved in the DM formation (Poerio et al. 2019).

6. Chemical methods

6.1. Coagulation and flocculation

Coagulation and flocculation methods are used during pre-treatment in WWTPs to form larger contaminant particles that can be separated more easily. These processes involve iron- and aluminum-based salts and organic coagulants to remove suspended solids, e.g. phosphorus (Padervand et al. 2019, Rajala et al. 2020). Coagulation is a widely used technology also in drinking water treatment (Wang et al. 2020, Shahi et al. 2020).

The behavior of MPs during coagulation and flocculation processes has recently been investigated to optimize the removal of MPs. Ma et al. (2019a, 2019b) studied ferric chloride and aluminum chloride treatment in removal of PE microparticles in a synthetic drinking water matrix. Then, Al-based coagulant showed better MP removal efficiency (36%) than Fe-based coagulant (17%). The addition of polyacrylamide (PAM) further increased coagulation.

The application of commonly used inorganic and organic coagulants to remove MPs as a tertiary wastewater treatment was recently investigated by Rajala et al. (2020). MP removal was studied by spiking secondary WWTP effluent with a known number of PS spheres less than 10 µm in diameter. Ferric chloride, polyaluminum chloride, and cationic polyamine were applied for coagulation/flocculation, followed by settling. MP concentrations were recorded with flow cytometry. With ferric chloride, the minimum MP concentrations after coagulation/flocculation were below the limit of detection, corresponding to a removal efficiency above 99.4%. With polyaluminum chloride, the maximum removal obtained was 98.2%. Polyamine was less efficient that the inorganic coagulants. Interestingly, the MPs were removed more efficiently than other particles in the wastewater matrix.

In addition to dosage and type of coagulant and flocculant aids, and pH, coagulation methods are dependent on size, shape, and chemical composition of MPs. According to Bui et al. (2020), the number of studies related to this technology for MPs is still limited, especially for wastewater treatment systems. It is essential that future studies concentrate on finding the best coagulant/flocculant aids and their optimum conditions for MP removal.

6.2. Electrocoagulation

Instead of chemical coagulation, electrocoagulation (EC) uses metal electrodes to produce coagulant electrically. Electrocoagulation has been shown to effectively remove dyes, heavy metals, oil and antibiotics (Perren et al. 2018, Zhang et al. 2021). In EC, metal ions are liberated from sacrificial electrodes into the water stream via electrolysis. These ions then form coagulants in situ. The most commonly used coagulants produced by EC are formed by reaction of the metal ions, usually Fe^{2+} and Al^{3+}, with OH^- ions formed by electrolysis to produce metal hydroxide coagulants. These coagulants destabilize the surface charges of the suspended solids, breaking up the colloid or emulsion, which in turn allows them to approach each other close enough for van der Waals forces to take effect. Meanwhile, the coagulant forms a sludge blanket, which traps the suspended solid particles. The H_2 gas liberated in the electrolysis process then lifts the resultant sludge to the water surface (Perren et al. 2018).

Artificial wastewater containing PE microbeads of different concentrations was treated with EC by Perren et al. (2018). The effects of initial pH, NaCl concentration, and current density on removal efficiency were studied. EC was found to remove MPs in excess of 90% over pH values ranging from 3 to 10. The optimum removal efficiency of 99.2% was found at a pH of 7.5.

6.3. Sol-gel induced agglomeration

As an alternative for traditional flocculants, Herborg et al. (2018) developed a new approach to remove MPs from water using organosilanes (Figure 6). The organosilanes consist of one organic group and three reactive groups. Due to the interaction of the organic group and the surface of the MPs, the organosilanes attach to the surface of the MP particles and collect them in agglomerates in the first step of the fixation process. In the second step of the fixation, the three reactive groups form a solid hybrid silica gel that includes and fixes the MPs chemically driven by a water induced sol-gel process. During this sol-gel process, the reactive groups are hydrolyzed to highly reactive silanols, which subsequently condensate and form siloxane bonds (Sturm et al. 2021). The enlarged agglomerates formed can be separated much more easily from e.g. wastewater, since they float on the water surface (Herborg et al. 2018).

In studies with demineralized water, salt water and secondary wastewater effluent spiked with PE and PP MPs and treated with a mixture of organosilanes (PE-X), removal rates of 97.5, 99.4 and 98.7%, respectively, were achieved (Sturm et al. 2021). No negative effects of temperature on removal were observed. PE-X showed no dissolved residues and therefore is considered well suited for the application on technical scale without posing any risk of introduction of organosilanes into the environment or technical processes (Sturm et al. 2021).

The chemical composition and surface chemistry of MPs have a strong influence on the removal process and physical interaction with the organosilanes. The removal efficiency of MPs based on different polymer types decreases with the increasing polarity of the polymer. Highly polar polymers, e.g. PVC, can be removed more efficiently by increasing the polarity of the organic group. However, this leads to a reduced effectiveness towards non-polar polymers. These results show that the organosilanes can be adapted specifically to improve the removal of certain polymer types by adjusting the organic group to the surface chemistry of the polymer. The high variability and modifiability of organosilanes makes them a very promising substance class for this challenge. Another alternative to increase the efficiency is using higher concentrations of organosilanes. Further studies should focus on the combination of different organosilanes for an effective removal of mixtures of polar and non-polar polymers (Sturm et al. 2021).

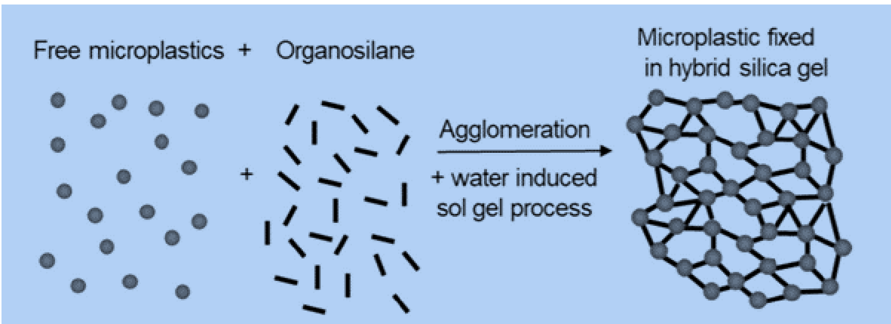

Figure 6. Agglomeration-fixation reaction for removal of microplastics from water using organosilanes. Organosilanes attach to the surface of MP particles, collect them in large agglomerates and chemically fix them by forming a solid hybrid silica in a water induced sol-gel process (Sturm et al. 2021).

6.4. Ozonation

Ozonation can be used in WWTPs as part of the tertiary treatment to disinfect the effluent and to remove residues that pass through from the coagulation process. Ozonation can also break down the polymer that constitutes MPs into functional groups that contain oxygen (Bui et al. 2020). Ozonation was studied in a WWTP as a final unit operation by Hidayaturrahman & Lee (2019). At this treatment step, 89.9% of remaining MPs were removed.

According to Bui et al. (2020), one of the factors limiting the application of ozonation for the removal of MPs might be the operating cost. Although the degradation rate increased dramatically in shorter operating times, this process requires a large amount of ozone dosage. In addition, during ozonation, if the treatment does not take place completely, intermediate products can be formed that can adversely affect human health and the ecosystem.

6.5. Dissolved air flotation

In dissolved air flotation, water is saturated with air at high pressure. In flotation tank, the released air bubbles in dispersed water adhere to the suspended solids causing them to float to the surface where it is removed by skimming. The air flotation parameters such as bubble size can be adjusted according to the characteristics of the particles to be removed (Talvitie et al. 2017a, Zhang & Chen 2020). Dissolved air flotation for MP removal as a full-scale tertiary treatment was examined in a WWTP by Talvitie et al. (2017a). To enhance flocculation, polyaluminum chloride was used in the flotation tank. Then, a MP removal rate of 95.0% was obtained.

7. Biological methods

7.1. Microbial methods and methods based on higher marine organisms

Biological methods for MP capture and/or degradation based on activities of microorganisms and higher organisms have been explored by several research groups.

Extracellular polymeric substances (EPS) produced by microorganisms consist of carbohydrates and proteins as the major components, and the complex molecules form tangled or covalently crosslinked networks, biofilms (Sheng et al. 2010). These viscous, gel-like structures can trap or bind various suspended solids. This makes them potential candidates for alternative solutions to inorganic salts and synthetic polymers as eco-friendly bioflocculants in wastewater treatment (Cunha et al. 2020). The potential of these microbial EPS materials for MP bioretention has recently been studied.

The bioflocculant activity of EPS produced by a freshwater microalga *Cyanothece* sp. strain under nano- and micro-size PS bead exposure conditions was investigated by Cunha et al. (2020). EPS production was significantly higher when the microalga was exposed to 10 mg/L of PS nanoplastics compared to exposure level of 1 mg/L, suggesting the EPS acting as a self-protecting mechanism for the microalga. The EPS produced by *Cyanothece* sp. displayed high bioflocculant activity already at the low concentrations tested and was suitable for nanoplastics and MPs aggregation. According to the authors, the results highlight the promising potential for microalgal-based biopolymers to replace the traditional flocculants used in wastewater treatment, in addition to the ability to aggregate the <300 µm MP fraction that many conventional removal methods in wastewater treatment are unable to remove. However, optimization of the cultivation and EPS formation conditions is needed to enhance production efficiency for potential applications (Cunha et al. 2020).

In a recent study by Liu et al. (2021), an interesting bioaggregation process for capturing MPs and then releasing them was developed. The process is based on EPS biofilm produced by an engineered *Pseudomonas aerigunosa* bacterium strain. MPs in freshwater and seawater were trapped and aggregated in the bacterial EPS network with a removal efficiency of over 80%. The MP-laden EPS together with the bacterial cells deposited at the bottom of the bioreactor for isolation. Then, treatment of the EPS matrix with an inducible stimulus dispersed the biofilm and the MPs were released for recovery (Figure 7). This was mediated by the bacterial production of biofilm degrading glycosidases and proteases and induced by L-arabinose addition. Although this capture-and-release bioaggregation method is not directly usable for industrial applications due to safety concerns linked to genetically modified bacteria, this work provides the basis for future studies in identifying probiofilm-forming isolates from sewage which can aggregate MPs efficiently (Liu et al. 2021).

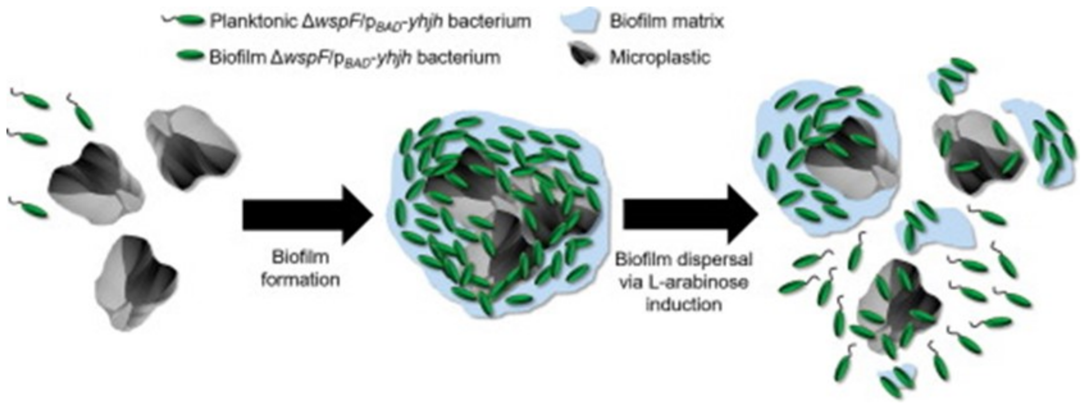

Figure 7. Schematic illustration of 'capture-and-release' mechanism of engineered *Pseudomonas aerigunosa* (Liu et al. 2021).

The bioaccumulation of nanoparticles into mucus materials produced by different jellyfish species was demonstrated by Patwa et al. (2015). Jellyfish mucus is a hydrogel composed mainly of water (95%), mucins (3%) and lipids and nucleic acids (2%). Lengar et al. (2021) investigated jellyfish mucus as a new bioflocculent material capable of retention of PS MPs in aqueous
environments. Mucus material was collected from different jellyfish species and then used to trap fluorescently tagged PS microbeads. When 8000 PS microbeads/mL were added to the mucus suspension, approximately 50% were retained in the mucus. The viscosity and therefore the MP removal efficiency were highest with freshly prepared mucus material. Confocal laser scanning microscopy of the MP-mucus aggregates revealed that PS microbeads were physically trapped in the gel structure and that direct chemical interactions were not the main driving forces of MP retainment. For development of potential processing steps for the removed MPs the authors suggest biodegradation of the MP-mucus aggregates or the use of degradative enzymes (Lengar et al. 2021).

The ability of Red Sea giant clams *Tridacna maxima* to remove PE microbeads from seawater and their importance as a sink for this pollutant was investigated by Arossa et al. (2019). The study revealed that the removal occurs through two independent processes: an active ingestion of the plastic beads and a dominant, passive process involving the attachment of beads to the shell. Further studies are needed to clarify the actual role of passive removal in the natural environment. However, the results support the suggestion that the massive coral reefs of the Red Sea may act as effective filters, possibly dominated by passive removal processes, accounting for the low MP concentration in the Red Sea (Arossa et al. 2019, Padervand et al. 2020).

The potential of marine microorganisms and zooplankton to facilitate the biological degradation of MPs in seawater and coastal sediments has been reviewed e.g. by Padervand et al. (2020). Biological degradation has been confirmed to be able to remove MPs at low concentrations. However, the data could not convince the authors to consider "ingestion" as a MPs removal strategy to treat the MP pollution (Padervand et al. 2020).

Bacillus strains isolated from mangrove sediments were tested for their biodegradability potential of different UV-treated MPs. Degradation was monitored by recording the weight loss of MPs. The calculated weight loss percentages of the MP particles by a *B. cereus* strain after 40 days were 1.6%, 6.6%, and 7.4% for PE, PET, and PS, respectively. The highest value for PS corresponds with the shortest degradation half-life, 363 days (Auta et al. 2017) indicating the slow rate of microbial degradation of MPs.

7.2. Vegetation-based methods

Information on the uptake and accumulation of MPs by higher plants is still limited. However, the ability of different plants to accumulate submicrometer- and micrometer-size plastics from soil has recently been demonstrated. First, 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 (Ebene et al. 2019, Li et al. 2020).

Potentially useful phytoremediation techniques for remediation of MP contaminated soils or water include phytoextraction and phytofiltration. In phytofiltration (rhizofiltration), plants are utilized to take up contaminants from groundwater and aqueous waste streams. The contaminants are either adsorbed onto the root surface or absorbed by the plant roots. Once the roots are saturated, they are harvested and disposed of safely (Ebene et al. 2019).

The potential of higher aquatic plants for MPs removal in WWTPs has recently been reviewed by Masiá et al. (2020). They suggest that the phytoremediation approach could be used for MPs retainment both in the solid and in the liquid phase, by growing these plants in WWTPs. Seagrasses and seaweeds seem to be suitable candidates for treating MP containing effluents. In seagrasses and seaweeds, MPs retention may take place in different ways, with the particles accumulating on the blades and in their associated microbiota (Goss et al. 2018, Masiá et al. 2020). According to Masiá et al. (2020), plants could be grown in WWTPs from the stage at which MPs retention is efficient, and the parts of plants where MPs are retained, sediments, or the whole plants, could be harvested for disposal of the MPs.

A Finnish company InnoGreen Ltd investigates how effectively MPs in urban runoff can be filtered by an outdoor green wall. A modular green wall was built in Helsinki next to the Ring road I and the road runoff water was directed through the green wall. The study was one of the Speedy Experiments of the Baltic Sea Challenge. Based on preliminary results, the green wall system retained some of the MPs from the runoff water (InnoGreen 2021). Future studies may reveal the full potential of this management method for urban runoff and the role of plants in MPs removal.

8. Comparison of different MP removal technologies and methods

An overview of existing and emerging technologies and methods for MP removal is presented in Table 1. Technologies with high removal efficiencies and/or future potential were selected in the Table.

When developing removal technologies for MPs particles, life cycle assessment (LCA) should be applied in evaluating and comparing the environmental impacts (Zhang et al. 2021). Also, techno-economic analysis for these emerging technologies and methods is essential to reveal the technical and economic feasibility of the solutions under development.

Table 1. Comparison of various removal technologies and methods for microplastics (modified from Padervand et al. 2019, Zhang et al. 2021). ND, no data.

Method	MP removal efficiency (%)	Comments	Selected references
Sand filtration	74–97	Simple operation, low cost Efficiency for small MP particles not yet clear	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 -> reduce 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	ND	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, simple mechanical devises, low energy consumption Large quantities of chemicals needed, 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, no requirement of 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 ja surface properties of MP particles	Herborg et al. (2018), Sturm et al. (2021)
Bioagglomeration (bio-flocculation)	50–80	Bioflocculants produced by microbes and jellyfish Bench-scale results reported only	Cunha et al. (2020), Li et al. (2021), Lengar et al. (2021)
Retention ponds	85	Used for stormwater management Research data on MP removal efficiencies still limited	Borg Olesen et al. (2019)
Bioretention systems	70–84	For stormwater management	Smyth et al. (2021), Lange et al. (2021)
Phytofiltration (vegetation-based accumulation)	ND	Research data still very limited	Ebene et al. (2019), Masiá et al. (2020)

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

In the above-reviewed studies on various technologies and methods for MPs removal from wastewater and stormwater, no concrete treatment methods for matrices enriched with MPs were developed or discussed. These materials include sewage sludge, pond sediments, sand, plant biomasses and membrane filtration retentates. In this chapter, possible options for final disposal or treatment of these materials are discussed.

9.1. Treatment and use of sewage sludge

Sewage sludge contains organic matter and nutrients (N, P, K), which improve soil structure and nutrient content, and is therefore commonly used as biosolid/soil amendment either in agriculture or landscaping. Sewage sludge directive (86/278/EEC) both promotes the use of sewage sludge in agriculture, but also regulates its use to prevent harmful effects due to micro-biological or chemical contamination. After the directive came in force 1986, there has been scientific progress and technological development. Thus, the directive is currently under revision (EC 2021).

The suitability of sewage sludge as soil amendment is improved through treatment methods such as lime stabilization, anaerobic digestion, composting and thermal drying, which however do not decrease the MP concentration in the sludge. Mahon et al. (2017) demonstrated that approximately 99% of MPs can persist in sludge, even after several treatment stages, such as lime stabilization or anaerobic digestion.

The practices for the use of treated sewage sludge vary between countries. Rolsky et al. (2020) reported disposal alternatives for twelve countries (Figure 8). 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, the MPs are present in the sewage sludge in high concentrations. However, the current treatment methods for biosolids are insufficient to degrade MPs. One the other hand, it is neither required in the legislation. When the compost standards were compared within Europe, America and Australasia, 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, in some countries the threshold is 10 to 15 mm (e.g. Spain and New Zealand), while in some other European countries and in USA plastic is not mentioned in the requirements for impurities inspection.

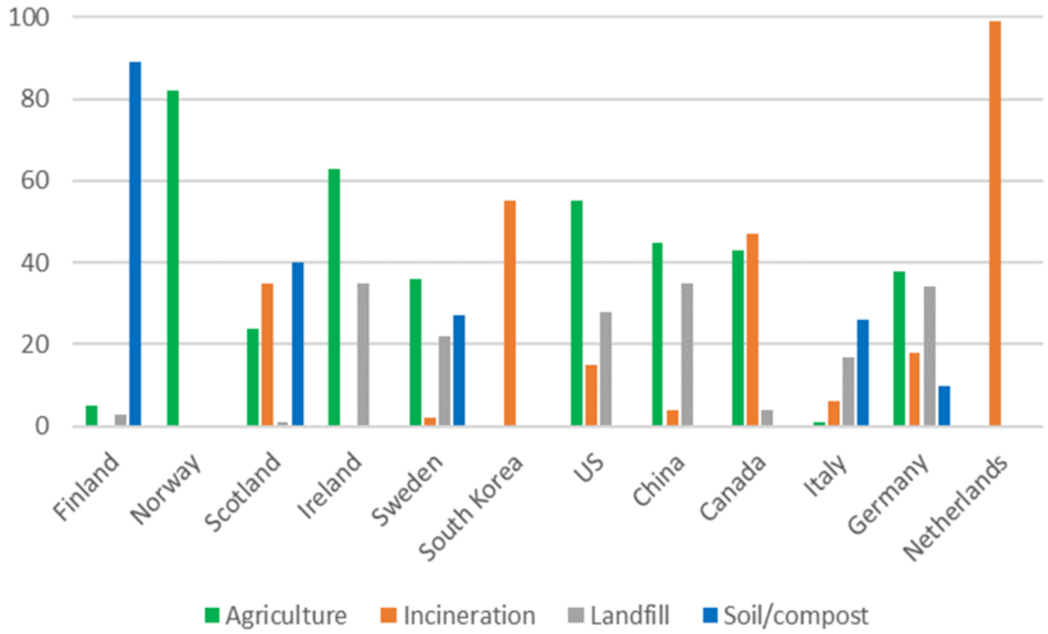

Figure 8. Reported percent of treated sewage sludge usage per country (Figure based on data from Rolsky et al. 2020).

The faith of MPs in the soil is not well understood. Studies have shown that MP particles were identifiable in the soil column over 15 years after the initial application and it has also been suggested that they can last up to 100 years because of reduced light and oxygen, conditions which in higher amounts are normally associated with the degradation of MPs (Zubris & Richards 2005, Ward et al. 2019). Furthermore, Nizzetto et al. (2016) found that only 16–38% of MPs entering the soil through soil application will remain in the soil, and most of the MPs will eventually migrate from the soil into receiving water bodies. In addition to plastic polymers, MP particles carry on their surface heavy metals, organic pollutants, and antibiotics (Figure 9). Thus, the long-term sludge land application may lead to accumulation of MPs and other contaminants which they are carrying to agricultural soils, migration to groundwater, phytotoxicity and degradation of soil quality (Zubris & Richards 2005).

To 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. However, other methods for sewage sludge treatment, which could retain the organic matter and the nutrients for land application, are being developed. One solution is to improve the MPs removal during grease removal stage of WWTP and to treat the grease separately for preventing large number of MPs entering the waste sludge (Sun et al. 2019). On the other hand, pyrolysis techniques, including thermal pyrolysis, catalytic pyrolysis and microwave assisted pyrolysis, can decompose the long chain polymers into oligomers. So far, this method has only been applied to treat macroplastic waste. However, the recent development of co-pyrolysis with biomass may provide a solution for treating MPs-containing sewage sludge (Sun et al. 2019).

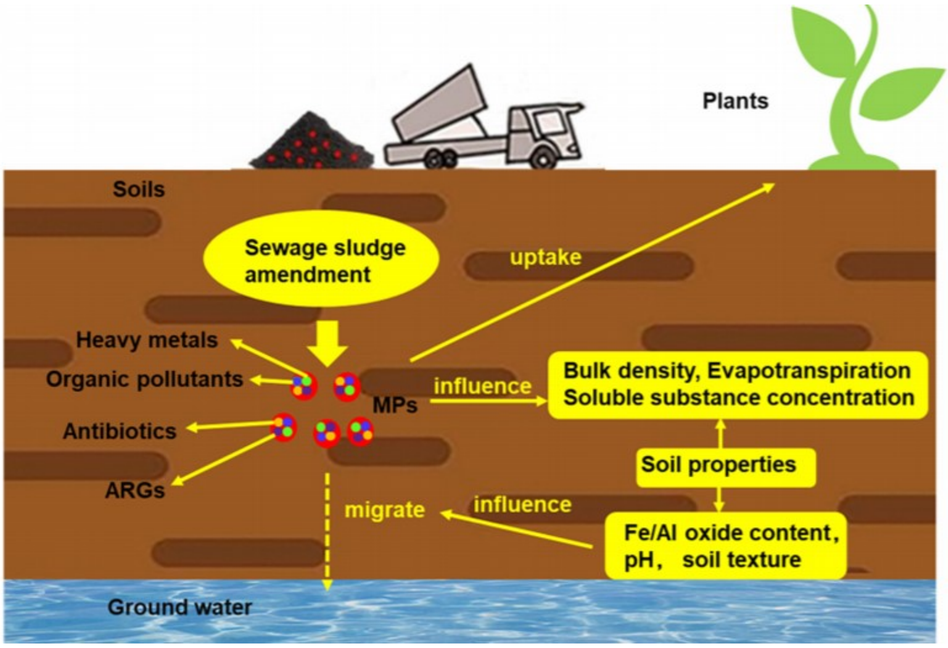

Figure 9. Environmental risks in soil supplementation with MP-enriched sewage sludge (Gao et al. 2020).

9.2. Treatment of extracted MPs or MP-enriched materials

Most research on MPs removal is focused on WWTPs where most MPs end up in sewage sludge. However, also stormwater contains significant amounts of MPs and various filtration methods are being developed also for stormwaters. Depending on the filtration method, the MPs are either concentrated in the filter matrix, such as sand or biochar, or in the sludge cake from disc and membrane filters. The reviewed literature focusing on the MP removal efficiencies of various technologies does not include data on filter material regeneration or disposal, or the treatment of the filter cake. However, the final disposal methods are crucial to avoid MPs re-entering the environment and should be considered simultaneously when developing new methods. Some suggested final disposal methods are incineration, anaerobic digestion, thermolysis/pyrolysis, and chemical recycling (Zhang et al. 2021).

Zhang et al. (2021) also suggest that density separation, which is currently used only for sample analysis, could be used as a treatment method to separate MPs from solid matrices. Density separation is based on density differences between MPs and surrounding environments. Despite a large variation, the density of conventional plastic is between 0.90–1.45 g/cm^3, whereas densities of solid matrices, such as soil and sediment, are up to 2.65/cm^3, i.e. largely higher than plastics (He et al. 2021). Saturated salt solutions are usually utilized as extraction solution to float MPs into the supernatant, while soil or sediment sinks to the bottom. Other measures including aeration, stirring and centrifugation are necessary during this process, which can largely facilitate MPs isolating from other impurities (He et al. 2021). For a large-scale application, the MPs removal by density flotation could be intensified by technologies borrowed from the minerals engineering, such as a jig, a hydrocyclone, a shaking table, and a spiral chute (Zhang et al. 2021).

10. Conclusions

In this review, existing and emerging technologies and methods for MPs removal especially from urban aquatic environments are presented. In recent years, physical, chemical and biological technologies and methods for MPs removal have been investigated and developed mainly for wastewaters. 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 discussed in the review.

In recent years, the capability of various treatment processes utilized in WWTPs to remove MPs from wastewater has been increasingly investigated. It is evident, that modern secondary or tertiary WWTPs remove MPs efficiently from wastewater, although the treatment processes have not been specifically designed for MP removal. However, as vast volumes of wastewaters flow through WWTPs, still significant amounts of MPs are transported in the effluents to receiving aquatic bodies, e.g. to the Baltic Sea. Therefore, wastewater treatment processes need to be further optimized to retain MPs more efficiently without compromising other water treatment goals. On the other hand, present wastewater treatment technologies and methods are replaced with novel technologies to better meet the stringent requirements for treated waters, 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 in conventional activated sludge process.

The majority of stormwaters ends up in aquatic environments untreated or only partially purified. Only recently the MP loads in stormwaters have been fully recognized and especially the high amounts of traffic MPs in road runoff are being revealed. 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. Recently, retainment of stormwater MPs has been the subject of studies focusing on sedimentation ponds, filtration and bioretention systems. New and innovative MP removal technologies and methods suitable especially for stormwaters including urban snow meltwaters are still needed and the MP removal efficiency of these methods should be demonstrated in pilot studies. Also, techno-economic analysis and LCA for these emerging technologies and methods compared with existing technologies are essential to evaluate the technical and economic feasibility and the environmental impacts of the processes under development.

MPs 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.

Finally, 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 urgently needed to avoid mere shifting of MPs and their effects from one environmental compartment to another.

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