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Review

Between source and sea: The role of wastewater treatment in reducing marine microplastics

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ABSTRACT

Wastewater treatment plants (WWTPs) are a focal point for the removal of microplastic (MP) particles before they are discharged into aquatic environments. WWTPs are capable of removing substantial quantities of larger MP particles but are inefficient in removing particles with any one dimension of less than 100 µm, with influents and effluents tending to have similar quantities of these smaller particles. As a single WWTP may release >100 billion MP particles annually, collectively WWTPs are significant contributors to the problem of MP pollution of global surface waters. Currently, there are no policies or regulations requiring the removal of MPs during wastewater treatment, but as concern about MP pollution grows, the potential for wastewater technologies to capture particles before they reach surface waters has begun to attract attention. There are promising technologies in various stages of development that may improve the removal of MP particles from wastewater. Better incentivization could speed up the research, development and adoption of innovative practices. This paper describes the current state of knowledge regarding MPs, wastewater and relevant policies that could influence the development and deployment of new technologies within WWTPs. We review existing technologies for capturing very small MP particles and examine new developments that may have the potential to overcome the shortcomings of existing methods. The types of collaborations needed to encourage and incentivize innovation within the wastewater sector are also discussed, specifically strong partnerships among scientific and engineering researchers, industry stakeholders, and policy decision makers.

1. Introduction

Since the 1940s, plastics have revolutionized society to the extent that most people now use and depend on plastic products on a daily basis. At the same time, there is mounting concern that the production, use and disposal of plastics may pose risks to the environment and human health (Thompson et al., 2009b). Plastics have become ubiquitous because they are inexpensive relative to many other materials, generally durable and easily adaptable for manufacturing many kinds of products. Plastics are made from petrochemical-compounds, usually in combination with additives such as fillers, plasticizers, dyes, stabilizers, lubricants and foaming agents (Cole et al., 2011; Hollman et al., 2013). Approximately 30% of all plastic ever produced is estimated to be currently still in use, but the durability of plastic products no longer being used means they continue to exist in some form (often as waste), some of which eventually reaches the seas and oceans (Geyer et al., 2017; Kubowicz and Booth, 2017; OSPAR, 2009). A proportion of this marine plastic waste is in the form of small particles known as microplastics (MPs). There are several size classifications for MPs, although it is generally accepted that they are less than 5 mm in size. Some

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definitions place a lower bound of 1 μm, with particles smaller than this being classified as nanoplastics (NP) (Cole et al., 2011; Hollman et al., 2013). A further refinement has been proposed with three classes, mesoplastic (1 mm–2.5 cm), MP (1–1000 μm) and NP (<1 μm) (Frias and Nash, 2019; Hartmann et al., 2019).

MPs that are deliberately manufactured and used to make other products are considered primary MPs. Those that result from the breakdown of larger plastic items are considered secondary MPs. The routes by which primary and secondary MPs reach marine environments have been investigated (Fendall and Sewell, 2009; GESAMP, 2015; Geyer et al., 2017; Gregory, 1996; OSPAR, 2009; Zitko and Hanlon, 1991), with the main ones considered as:

i. Items discarded on land that have broken down into secondary MP and are washed by rain or transported by wind into the sea.
ii. Larger Items disposed of on land and washed by rain and wind into the sea where they eventually break down into secondary MP.
iii. Primary MP inadvertently lost during production, transportation and subsequent use and entering the waste stream; or
iv. MPs discharged from wastewater treatment plants (WWTPs):
   a. Via treated wastewater (WW) discharged into waterways
   b. Via sewage sludge used in agricultural fertilizer and other applications.
   c. Via wear and tear of plastic components used in the WWTPs.

As there are different routes by which MP waste from different sources reaches the seas and oceans, reducing the flow of such small plastic particles requires a multi-faceted approach. Of the four routes described above, the first two are widely acknowledged as the major sources of marine MPs and have attracted much of the attention and effort related to reducing plastic pollution, including reducing the quantity of plastics manufactured and used as well as better waste management approaches (Booth et al., 2018; Browne et al., 2011; Jambeck et al., 2015; Lam et al., 2018; Sundt et al., 2014; Thompson, 2015). Less is known about the quantities of MPs released via the third route, but it has been identified as a target for better management in supply and processing chains, for example by reducing spillage and finding alternatives to MPs added to consumer products (Government of Canada, 2015; Sundt et al., 2014; UK Government, 2018). The fourth route has only recently begun to receive attention, but it appears that treated WW effluent may make a substantial contribution to aquatic and marine MPs (Sundt et al., 2014). WWTPs are focal points in concentrating large amounts of MPs from urban sources. At the same time, these utilities act as a gateway for MPs from domestic, commercial, industrial and other sources, although the ultimate fate of the MPs depends on whether they remain in the treated effluent. While large quantities of MPs are removed from the treated WW (Koelmans et al., 2019) and retained in sewage sludge, wastewater treatment (WWT) does not target MPs specifically. As a result, most WWTPs discharge effluents containing MPs into rivers, lakes and groundwater that eventually reach marine water bodies. A number of recent reviews have focused on the fate and behavior of MPs in WWTPs, investigated different sampling and analysis approaches or summarized MP effluent (water and sludge) concentrations (Enfrin et al., 2019; Gatidou et al., 2019; Koelmans et al., 2019; Mahon et al., 2017; Murphy et al., 2016; Sun et al., 2019; Zhang and Chen, 2020; Ziajahromi et al., 2017; Li et al., 2018, 2020). Only a small number of reviews and studies have attempted to compare the efficiency of different technologies for removing MPs from effluent streams (Sun et al., 2019; Talvitie et al., 2017a; Zhang and Chen, 2020), but none included bio-based filters or discussions of the role of policy and innovation in bringing about changes in WWT practices.

It is important to note that the sludge produced as a by-product of WWT in fact contains most of the MPs removed from treated WW. If not properly managed, this sludge can itself be a source of MP pollution to soil, air and in turn indirectly to surface water. Nevertheless, WW and sludge treatment are separate processes and the current study focuses on the former. We first summarize the state of knowledge regarding MPs in the environment and the contribution of WWT effluents to the problem, followed by a discussion of the role of WWTPs in reducing the quantities of MP reaching the natural environment through effluent releases. We then examine and compare current technological innovations to reduce MP concentrations in effluents, including a previously undocumented and unique bio-based treatment technique that shows great potential. In a novel approach, we then set the knowledge gathered within the context of current policy discussions and highlight possible limitations and opportunities going forward, including highlighting knowledge gaps that are currently hindering said policy development for effective regulation of MPs in WWTP effluents.

2. State of knowledge

2.1. Prevalence of MPs in marine ecosystems and food webs

Owing to their light weight and persistence, MPs can be transported over long distances and accumulate in most marine environmental matrices; from urban beaches to sediments, as well as remote polar and central ocean regions (Imhof et al., 2013; Ryan et al., 2009; Thompson et al., 2009a). Estimates of the amount and distribution of MPs in marine environments are variable. The number of MP particles in oceans and seas around the world has been estimated to range from 15 to 51 trillion (Baztan et al., 2017; Bergmann et al., 2015; Eriksen et al., 2014; Jambeck et al., 2015; Jang et al., 2016). It has been reported that 15% of MPs are located in the water column, up to 70% have settled on the seafloor and the remainder is washed ashore (Barnes et al., 2009; Hammer et al., 2012). Another recent study suggested that over 90% of marine MPs have accumulated in sediments (Booth et al., 2018). Accumulations of redeposited particles have also been observed on shore in sand and in "plasticrusts" of small plastic debris in rocky intertidal zones (Gestoso et al., 2019).

MPs are found in marine organisms from most trophic groups, sizes and life stages (Barboza et al., 2019; Bergmann et al., 2015; Booth et al., 2018; GESAMP, 2015; Mathalon and Hill, 2014). Detection is most frequent in digestive tracts, but there is increasing evidence that extremely small (nano)particles may cross biological barriers and accumulate in organs and tissues of multicellular biota, including humans (Brennecke et al., 2015; Collard et al., 2017). The size and shape of ingested plastic particles appear related to the taxon, body size, and life stage of marine organisms (Cole et al., 2013). There is also evidence that certain organisms (e.g. Antarctic krill, *Euphausia superba*) are able to alter the size of ingested plastic, fragmenting them into sub-micro particles (Dawson et al., 2018). With decreasing particle size, the likelihood of being ingested by small lower trophic organisms increases and with it, the risk of wider food web impacts. For this reason, there is concern that extremely small particles ingested by suspension and deposit feeding organisms may pose risks to these essential units within the food web either by directly affecting the ingesting organisms or by widespread distribution throughout the foodweb (Gies et al., 2018). Evidence from the higher end of the trophic spectrum includes preliminary results from an ongoing 8-country pilot study showing that MPs are present in human stools, a clear indication that people are ingesting MPs (Schwabl et al., 2019).

2.2. Impacts on marine ecosystems and organisms

The prevalence of marine MPs raises concerns regarding environmental quality and potential adverse mechanical, chemical and microbial impacts on organisms and food webs (Anderson et al., 2016; Auta et al., 2017; Barboza et al., 2019; Lusher, 2015; Rochman et al., 2015, 2016; Solomon and Palanisami, 2016; Van Cauwenberghe et al., 2015a, 2015b; Wright et al., 2013a, 2013b). Mechanical effects, observed in several species are believed to stem from the size and quantity of ingested materials and effects include hindering mobility, clogging of the digestive tract and internal abrasion (Setälä et al., 2016). Reduced nutritional status and weight loss have been observed in lugworms whose food intake was impaired by the presence of MPs and several fish studies report intestinal alterations associated with ingestion of MPs (Barboza et al., 2018; Besseling et al., 2013; de Sá et al., 2015; Oliveira et al., 2013; Pedà et al., 2016). Concerns for chemical effects stem from the fact that monomers, polymers and other chemicals may migrate from MPs into the environment or directly into ingesting organisms. Many of the plastic compounds detected in marine organisms are the same as those found in plastic packaging. Groh et al. (2019) and Geueke et al. (2018) found 68 environmental toxins and 63 human toxins in the approximately 900 chemicals most likely to be found in plastic packaging and many of these have been shown to migrate from the plastic to other media (Geueke et al., 2018; Groh et al., 2019). Adverse health impacts associated with chemical exposures include endocrine disruption and hepatic and oxidative stress in fish exposed to MPs (Barboza et al., 2018; de Sá et al., 2015; Oliveira et al., 2013; Pedà et al., 2016).

In some cases, adverse health effects cannot be attributed definitively to chemical or mechanical mechanisms. Examples of this include energetic depletion and reduced reproduction and growth rates in copepods and in other planktonic animals exposed to MPs (Cole et al., 2015; Della Torre et al., 2014). It has also been proposed that MPs may serve as vectors for pathogens, facilitating the transfer of bacteria and viruses by 'rafting' to new habitats or within food webs (Zettler et al., 2013).

The main human exposure pathway to MPs present in the marine environment is believed to be through the consumption of fish and seafood and processed foods, but additional research on the sources, intake and associated health effects is needed (Cox et al., 2019). A challenge for assessing human health impacts is that, many, if not most of the effects are probably at the sub-acute level, with morbidity appearing only after extended periods of exposure, making it very difficult to trace the links between exposure and eventual ill health (Wright and Kelly, 2017).

2.3. Marine MPs as contaminants of emerging concern

Marine MPs were first described and reported on in the early-mid-1970s, but the number of studies on MPs began to increase substantially in 2008 and continues to rise (GESAMP, 2015; Lusher et al., 2017; Ryan, 2015). A systematic search of the literature using the terms "microplastics" or "microplastic" in combination with the terms "marine" or "pollution" revealed that between 1991 and 2008, a maximum of one or two articles were published each year (Fig. 1). Between 2009 and 2014, 148 peer-reviewed papers were published. Between January 2015 and June 2019, the number grew by 1,701, indicating increasing concern supported by mounting evidence. The systematic search protocol can be found in the Supplementary Information.

According to Halden (2015), MPs are positioned at the second of eight stages of knowledge generation (See the Supplementary Information) for contaminants of emerging concern (CEC) (Halden, 2015). This means that there has been a progression from a low level of knowledge and awareness to preliminary evidence of a potential threat and knowledge gaps that need to be addressed in order to properly assess the risks and intervene appropriately (Halden, 2015). While the knowledge about the risks to ecological systems and human health may not meet the standards of evidence required for wide-ranging policy interventions, research has been prioritized by scientists across disciplines and institutional settings and preliminary management strategies regarding MPs are being discussed or implemented by decision makers. Policies banning personal care products containing MPs because of their contribution to marine MPs have been enacted by several governments, including the USA, Canada and the UK (114th Congress, 2015; Dauvergne, 2018; Government of Canada, 2018; Lam et al., 2018; Pettipas et al., 2016; UK Government, 2018; Xanthos and Walker, 2017). The European Union Marine Strategy Framework Directive (EU MSFD) defines MP as a pollutant. This requires all member states to establish and implement mitigation measures by 2020 (European Commission, 2018).

The growing concern is also reflected in several high-level international initiatives that recognize the complexity of the marine MP challenge, including the need for making decisions in the face of considerable uncertainty and the need to engage multiple stakeholders. Most of these initiatives also place MPs within the context of the entire plastic lifecycle, and therefore include reducing the quantities of plastics manufactured and consumed, removing existing stocks of MP particles in aquatic and marine environments and preventing MP particles from reaching these environments by improving waste management on land and in WW. The United Nations Environment Programme (UNEP) included the elimination of MPs in cosmetics as part of its global CleanSeas strategy, which also includes 13 non-binding resolutions on marine MPs signed by 193 nations (Ndiso, 2017; UNEP, 2017a, b, c). In 2018, UNEP's Global Plastics Platform was launched and the G7 published its Oceans Plastics Charter (G7, 2018; Walker and Xanthos, 2018). Several recent initiatives focus business stakeholders - the World Economic Forum's panel on ocean sustainability, the World Bank Group's PROBLUE Multi-Donor Trust Fund (MDTF) and the UN Global Compact Sustainable Ocean Business Action Platform (UN Global Compact, 2018; World Bank, 2018). One of the features of the business-oriented initiatives is that they recognize the need for innovation as part of sustainable solutions, including innovation in WWT. This recognition has yet to be translated into concrete regulation governing the operations of WWTPs.

Within Europe, for example, MPs are targeted within the Marine Strategy Framework Directive but not within the Urban Wastewater Treatment Directive that is the basis of the regulation for most European WWTPs (SAPEA, 2019). The systematic search of the literature revealed that globally, there is no jurisdiction that has specifications regarding the maximum level of MPs permitted in discharged WW. While WWT is highly regulated, the standards relate to water quality indicators such as concentrations of total organic matter, dissolved inorganic compounds, total suspended solids and nutrients, but not MP particles specifically. A key issue holding back regulation is available knowledge regarding the toxicity of MPs and how existing data have biased our view of the risk of

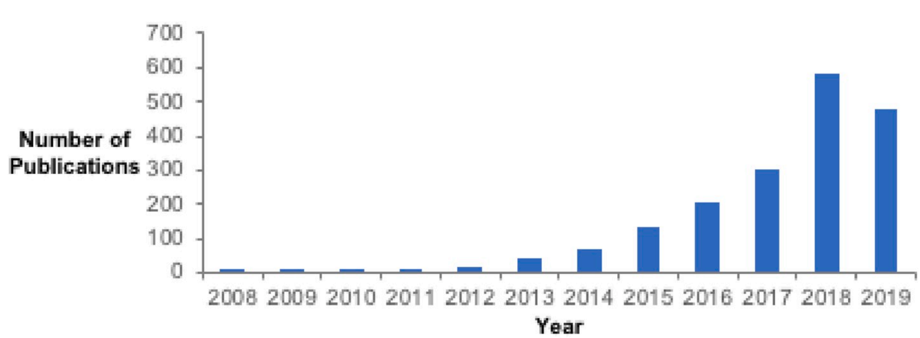

Fig. 1. Number of publications per year (Note, 2019 contains data for January–August).

MPs. Most studies that have shown effects in organisms from exposure to MPs have been at very high MP concentrations, several orders of magnitude above current environmental occurrence (Barboza et al., 2019; Everaert et al., 2018; Koelmans et al., 2017). Furthermore, most effects studies have used pristine spherical MP test materials of a single polymer type that do not accurately represent the partially degraded, irregular shaped MP mixture organisms encounter in the natural environment (Barboza et al., 2019; Pannetier et al., 2020). As a result, one main driver behind the current lack of regulation could be the absence of clear evidence for toxicity at environmentally relevant MP concentrations and for environmentally relevant MP particles, though more research needs to be conducted to make conclusions on this.

3. Wastewater as part of the problem and wastewater treatment as part of the solution

Typical WWT systems consist of successive treatment units of primary and pretreatment (physical screening and clarification), followed by a biological treatment unit (secondary treatment). Many systems also have a tertiary unit (i.e. sand filtration or membrane-based filtration), which is considered as a combined physicochemical process to assure high quality of the final effluent for either safe disposal or reuse in agriculture after proper disinfection. A simplified schematic representation of a treatment system is provided in Fig. 2.

The first or primary stage targets floatable and settleable solids. Raw influent WW flows through a grit chamber gated by a bar screen with a mesh of between 1 and 6 mm. Items too large to pass through the mesh are removed from the WW, indicating the largest MP particles (>1 mm) will be removed at this stage. Up to 35% of the total suspended solids (TSS) are removed at this stage after which the WW flows into primary settling tanks where 40–50% of the remaining TSS is removed from the bottom of the tank (US EPA, 2011). The TSS removed from the WWT stream becomes part of the sludge that is treated separately from the effluent WW. The second stage of WW treatment targets organic matter and nutrients using aerobic and anoxic biological processes. Solids are also targeted at this stage, usually through additional settling techniques such as coagulation and flocculation. During this stage MP particles would also be subjected to these processes, which result in partitioning to the sludge. The tertiary stage targets a variety of chemicals, pathogens and the remaining organic matter, nutrients, and solids (again relevant for any remaining MP). Included in the multiple techniques at this stage are disinfection (e.g. chemical, ultraviolet radiation) and chemical-physical separation (e.g. rapid sand or membrane-based filtration) to remove additional particles. The MP particles removed from the WW at all stages are subsequently incorporated with other substances removed to the sludge and treated separately.

Although the removal of MPs to sludge helps to reduce particles discharged into aquatic bodies, this process does not destroy MPs and the sludge can become a source of MPs to the environment when it is reused as biosolids or fertilizer (which it is in many parts of the world). The fate of MPs in sludge is an important issue for MP management. In this regard, several solutions have been proposed for reducing secondary MP pollution caused by sewage sludge (Zhang and Chen, 2020). For example, enhanced WWTP design at the grease removal stage has been suggested to improve removal of Low Density MPs and at the primary clarifier stage to increase settlement of High Density MPs (Yang et al., 2019), while the usage of flocculants (i.e. ferric sulfate and aluminum sulfate) has been proposed to produce large flocs that adsorb and accumulate MPs in the primary sedimentation tank (Murphy et al., 2016). Application of hydrophobic magnetic substances offers a potential mechanism to collect and remove the hydrophobic MPs (Grbic et al., 2019) and pre-treatment using pyrolysis technologies including thermal pyrolysis, microwave-assisted pyrolysis and catalytic pyrolysis has been suggested prior to sludge digestion (Undri et al., 2014). Finally, the removal of NPs has been suggested, for example in textile dyeing wastewater, using anaerobic digestion tanks that decompose the plastic into biogas (Feng et al., 2018). A focus of future research should be to find a way to remove or break down MPs during sludge treatment, so that they are not released into the environment.

The capacity of WWTPs to remove MPs from WW influent is a by-product of plants' design and several recent studies have quantified and categorized MPs in primary, secondary and tertiary WW and sludge. These studies were conducted on a variety of systems and employed various methods for sampling, sample preparation and analysis. While the results from the different studies may not be directly comparable, they do provide insights into the efficiency of current WWT processes on MPs under different real world and experimental contexts (Browne et al., 2011; Carr et al., 2016; Eriksen et al., 2013; Estahbanati and Fahrenfeld, 2016; Gies et al., 2018; Lares et al., 2018; Mahon et al., 2017; Mason et al., 2016; McCormick et al., 2014; Murphy et al., 2016; Sun et al., 2019; Talvitie et al., 2017a; Underwood et al., 2017; Ziajahromi et al., 2017). Table 1 provides examples of removal rates from a selection of these recent studies.

Gies et al. (2018) found large differences between visual counting methods and Fourier-transform infrared spectroscopy (FTIR) in distinguishing MPs from other particulate matter in water at each stage of treatment (Gies et al., 2018). Nevertheless, there is a general consensus that up to 88% of MPs in raw influent are removed during the primary and secondary treatment stages and up to a further 10% is removed in the tertiary stage (Carr et al., 2016; Murphy et al., 2016; Simon et al., 2018; Sun et al., 2019; Talvitie et al., 2015, 2017a). Interestingly, certain treatment types appear to exhibit varying efficiencies in removing differently shaped MP. Primary treatment using flocculation and sedimentation may be more effective in removing fibers and

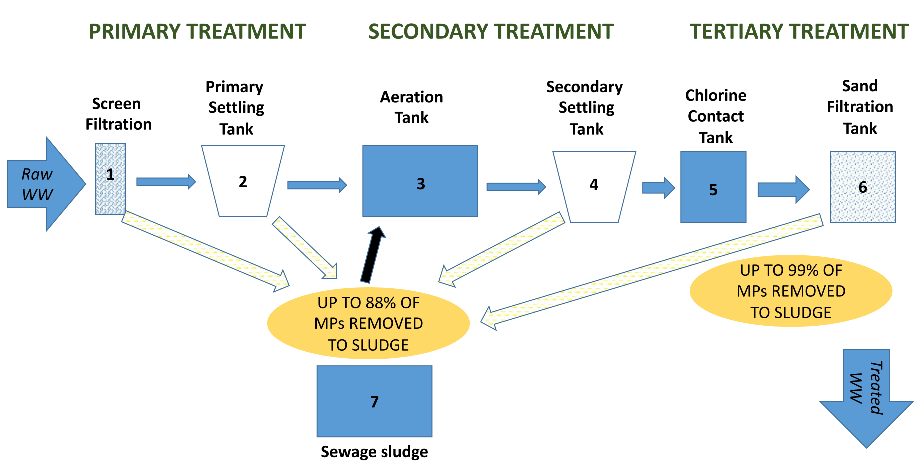

Fig. 2. Wastewater treatment process.

Table 1
Examples of MP removal rates for different WWTPs and treatment stages.

WWT Sites	Treatment Level	Removal Rate	Reference
Netherlands (7 WWTPs)	Tertiary	72%	Leslie et al. (2017)
Denmark (10 WWTPs)	Tertiary	99.7%	Vollertsen and Hansen (2017)
Australia (3 WWTPs)	Tertiary	>90%	Ziajahromi et al. (2017)
	Secondary	29%	
	Primary	17%	
Germany (1 WWTP)	Tertiary	97%	Mintenig et al. (2017)
USA (3 WWTPs)	Tertiary	99%	Michielssen et al. (2016)
	Secondary	96%	
UK (1 WWTP)	Secondary	98%	Murphy et al. (2016)
	Primary	78%	
USA (7 WWTPs)	Tertiary	90%	Carr et al. (2016)
Finland (1 WWTP)	Tertiary	99.8%	Talvitie et al. (2015)

Source: Hann et al. (2018)

skimming may be more effective in capturing bead shaped MPs, whereas irregularly shaped MP flakes may be more effectively removed during secondary treatment (Hann et al., 2018; SAPEA, 2019; Sun et al., 2019).

Of the remaining MPs in the final effluent, the reported concentrations from 15 studies representing 73 WWTPs range from 0 to 447 particles L-1 of effluent (Sun et al., 2019). Of these, reported daily emission data is available for 58 WWTPs, suggesting emissions of up to 1.83 x 1010 MP particles per day or up to an equivalent of 6.7 x 1012 MP particles annually from just one WWTP (Leslie et al., 2017). However, this amount will depend on the specific capacity of an individual plant (i.e. the amount of WW treated), the content of the raw influent and the efficiency of removal. For example, a small-medium sized WWTP that treats 30,000–50,000 m3/day of wastewater will contribute up to 1.34–2.24 x 1010 MP particles per day. Based on capacities of large WWTPs of up to 500,000 m3/day, emissions of MPs could then be expected to be one order of magnitude higher than for medium sized systems.

The particles released in the final effluent are generally smaller than the mesh size used in primary processing. Magnusson and Norén (2014) found that 70–90% of MP particles between 20 and 300 μm in raw influent were removed during treatment and 99% of particles larger than 300 μm were retained in a Swedish WWTP (Magnusson and Noré;n, 2014). Furthermore, Vollertsen and Hansen (2017) reported that the median size of particles (41.5 μm) in treated WWT was 20% smaller than that found in the raw influent (50 μm) (Vollertsen and Hansen, 2017).

Polyester microfibers and polyethylene microparticles are typically the most abundant MPs found in the final effluents of WWTPs (Browne et al., 2011; Lares et al., 2018; Murphy et al., 2016; Sun et al., 2019; Ziajahromi et al., 2017). This most likely reflects the fact that polyester is the most commonly used synthetic fiber in textiles and that polyethylene is the most prevalent polymer used in plastics manufacturing generally and that both are highly prevalent in WW as a result. A Danish study of 10 WWTPs also found that polyamide and nylon microfibers were highly abundant, suggesting a major input of MPs to WWTPs from domestic and industrial washing of synthetic textiles (Vollertsen and Hansen, 2017). An additional contributing factor to the prevalence of fibers in WW effluent may be their long thin shape, which may allow them to pass through even fine mesh filters in WWTPs (Sun et al., 2019). Other common MPs include polyethylene fragments with uneven shapes that have been attributed to personal care and household cleaning products containing MP particles (Talvitie et al., 2017b).

Notwithstanding the uncertainties regarding the exact types and quantities of MPs present in WW influents and effluents, current research points to relatively high capture rates. However, there remains a high potential for the release of large numbers of very small particles (low micron to nanometer in size) and fibers, as shown by the estimated annual release of up to 1010–1011 particles from a single WWTP (either small-medium or large size system). In addition, there is evidence that fiber-shaped particles in WW effluent may be more mobile than other MP particles. For example, one study traced MP particles through the effluent pipe from a Swedish WWTP to the sea and found that while all shapes were represented equally at the plant, only fiber shaped particles were present in seawater samples near the pipe outlet (Magnusson and Noré;n, 2014). From the standpoint of the marine environment, very small particles are of particular concern because of their potential for consumption by small biota and because in larger organisms these small particles are thought to have the greatest potential for true biological effect (i.e., transfer across biological membranes) and therefore the highest risk for eliciting toxicological effects (Hollman et al., 2013; Rochman, 2015).

4. Technological innovation in WWT

4.1. Existing innovation status for the capture of small particles

A review of technologies (Table 2) reveals that there is a lack of methods capable of efficiently removing very small plastic particles and fibers in a manner that is technically, environmentally and economically sustainable in industrial-scale WWTPs. Four technologies, Membrane Biological Reactor (MBR), Rapid Sand Filter (RSF), Dissolved Air Flotation (DAF), and Microscreen Filtration with Discfilters (DF), reviewed by Talvitie et al. (2017a,b) were effective for removing particles larger than 100 μm, but generally ineffective for fibers (Talvitie et al., 2017b). MBR combines biological processing of organics and nutrients in the raw WW with filtration via membranes to reduce the load of particles and microbes in subsequent treatment steps. Although this process is highly efficient (99.9% of all MPs are removed from the WW), some particles (especially fibers) tend to pass through with the treated WW. The RSF captures particles when the secondary WW effluent passes through the sand medium where collected particulate matter (including MPs) is removed by back-washing the sand; this process can remove as much as 97% of the MPs from the WW. DAF consists of pumping air into secondary effluent to cause particles and dissolved organic matter to float so that they can be skimmed off the surface 'scum' layer, thereby removing as much as 95% of the MPs from the WW. Microscreen filtration uses dedicated DFs to remove particles from the secondary WW effluent by simple mechanical filtration and harvesting of the collected particulate matter following backwashing of the filters. This filtration process can remove between 40 and 98.5% of the MPs from the WW. MBR and DAF are expensive to operate because of high capital or operating costs and energy consumption. MBR systems have particularly high maintenance costs because of fouling and biofouling problems. DAF was also found to be unsuitable for large WWTPs.

4.2. Future innovation status for the capture of small particles

At the experimental level, there have been varying degrees of success in removing particles at the smaller end of the size spectrum. One study reported low filtration resistance and trans-membrane pressure and easy cleaning in a Dynamic Membranes (DM) system; however, the system had high energy costs and low removal rates (Li et al., 2018). Another study tested enhanced flocculation/coagulation processes, but found that removal rates were low and restricted to bead-shaped particles while membrane fouling was also a problem (Ma et al., 2019). Although electrocoagulation (EC) appears to have very high removal rates, it requires continuous adjustment of pH levels and electrical current, and is unsuitable for the high-flow rates characteristic of most municipal systems (Perren et al., 2018). Early-stage experimentation of enhanced filtration with a back-flushing mechanism to prevent clogging of filters appears to have overcome the problem of clogging and shows some effectiveness in removing fibers; however, removal rates for very small particles remains uncertain (Beljanski et al., 2016). In a system currently

Table 2
Overview of technologies for removing MPs within WWTPs.

Technology	Strengths	Weaknesses	Reference
Membrane Biological reactor (MBR)	Reported 99.9% removal rate. Small footprint.	Expensive, fouling and biofouling problems, ineffective for removing particles <20–100 μm and fibers, high capital cost, high-energy requirement.	(Talvitie et al., 2017a, 2017b)
Rapid sand filter (RSF)	Reported 97.0% removal rate	Ineffective for removing particles < 20–100 μm and fibers.	
Dissolved air flotation (DAF)	Reported 95% removal rate	Ineffective for removing particles <20–100 mm and fibers. Cannot be deployed in large WWTPs. Expensive capital and operational cost.	
Disc filtration (DF)	Reported 40–98.5% removal rate	Ineffective for removing particles < 20–100 μm and fibers.	
Electrocoagulation	Reported 99.24% removal rate at pH = 7.5	Experimental (lab-scale) Applicable for beads only. Requires expensive, continuous adjustment of pH and electric current. May not be deployable in municipal-scale, high flow-through WWTPs.	Perren et al. (2018)
Gravity-powered filtration system	Specifically designed for MP removal	Experimental (lab-scale) Not yet tested on actual WW.	Beljanski et al. (2016)
Dynamic membranes (DMs)	low filtration resistance and low trans-membrane pressure (TMP); easily cleaned	Uncertain effectiveness, potentially high energy consumption.	Li et al. (2018)
Enhancement in flocculation/coagulation	Up to 40% removal efficiency	Experimental (lab-scale) Applicable for beads, increased membrane fouling in subsequent steps, low removal rate. It was tested only at lab-scale.	Ma et al. (2019)
Photocatalytic process	This technology is based on filtering WW using 1500 μm, 70 μm and 30 μm filters, followed by a photocatalytic process, supposedly to degrade these polymers.	Experimental (lab-scale). Length of process (175 h) is incompatible with current WWT processes.	Tofa et al. (2019)
Bio-based, jellyfish mucous filter	Cost-effective, requires little capital infrastructure, energy or other operating costs. Low footprint. Potential upstream job creation for fishers' supplying jellyfish Converts a nuisance species into something useful.	Experimental (lab-scale) • Removal rates vary by species of jellyfish supplying the mucus. • Optimal processing of mucus has yet to be determined. • Optimal deployment options within WWTPs has yet to be determined. • Ensuring supply of mucus may be challenging given fluctuations in the size of wild jellyfish populations. Options for deployment in WWTP are uncertain.	Unpublished

under development to address MPs in WWTPs, the EU H2020 *CLAIM* project is filtering WW using 1500 μm, 70 μm and 30 μm filters, followed by a photocatalytic process, designed to degrade these polymers. According to Tofa et al. (2019), the process required 175 h to degrade LDPE. Relative to the standard one-day hydraulic retention time (HRT) employed in most WWT systems, this is very long and would require significant capital investment to modify existing WWTP infrastructure.

Given the challenges associated with the approaches described above, some attention has been directed to bio-based alternatives derived from the mucus secreted by gelatinous zooplankton such as jellyfish and larvaceans. In *in situ* feeding experiments, giant larvaceans of the genus *Bathochordaeus* were able to trap MPs in the "mucous houses" they construct as part of their feeding process (Katija et al., 2017). In a laboratory setting, it was found that jellyfish mucus secreted as a stress response could be used to capture and concentrate gold nano-particles (Patwa et al., 2015). In both studies, inherent properties of the mucus rapidly capture micro and nano particles, causing them to be removed from aqueous suspension. The results stimulated thoughts of how this might be applied elsewhere.

The EU Horizon (2020) project *GoJelly*,[1] for example, assesses the potential for developing a filter based on jellyfish mucus within WWTPs to reduce the release of the uncaptured MPs to the environment. The characteristics sought are effective removal, energy and resource efficiency and low capital and maintenance costs. Two deployment options are being considered for application of the mucus filter; one during the primary treatment (in tank 2; Fig. 2), where the addition of the mucus-derived compound will act as a particle aggregator enhancing the settling process and facilitating the removal of MPs from the settling tank. The second option is as a pre-treatment to the tertiary stage sand filter (before tank 6; Fig. 2), where the mucus will facilitate the capture of MPs within the pores of the sand filter media. As a steady supply of mucus is crucial to the success of the system, developing methods of capturing different species of jellyfish, extracting their mucus and processing it has been a major focus of the work and includes examining the capacity within the fishing community to adapt existing practices to capture jellyfish (Liu et al., 2018; Nakar et al., 2011; Tiller et al., 2014, 2015). Table 2 provides an overview of the strengths and weaknesses of each technology described above.

[1] *GoJelly-A gelatinous solution to microplastic pollution* is a research consortium of 16 institutions funded by the European Union's Horizon 2020 program that has as one major objective of exploring ways of reducing the flux of MP waste to the sea by reducing the quantities of microplastic particles in treated wastewater effluent.

5. Discussion

WWT is recognized as an important element within the multifaceted sets of solutions needed to reduce the amount of MP waste entering marine environments. A growing number of trans-national policy initiatives (e.g. the G7 Charlevoix Declaration) contain clauses that recognize the requirement for research and development into better WWT, and the need to promote and support innovation to create economically feasible technological solutions (G7, 2018). Nevertheless, it has proven difficult to achieve broad consensus on international agreements. For example, only five of the G7 members plus the EU have ratified the agreement, while Japan and the USA have not done so (Benson Whalen, 2018). In addition, the Charlevoix Declaration, like many other recent high-level initiatives is voluntary. Others include the UN Global Compact on Sustainable Ocean Business Action, the High Level Panel for Ocean Sustainability, and the UNEP Clean Seas Imitative. Crucially, none of these are backed by concrete, binding policies having the type of regulatory infrastructure needed to enforce change, with the one exception being the World Bank's PROBLUE fund (Xu, 2016).

To be truly effective, policies must be binding and accompanied by enforceable regulations that will affect the operation of water utilities and that encourage technological change innovation needed to remove MPs from the treated WW stream (Magnusson and Noré;n, 2014). To the best of our knowledge, there is no requirement anywhere in the world for the removal of MPs during WWT (SAM, 2018). The reasons for the policy gaps may include the uncertainty related to the risks associated with MPs (reviewed above). As a result, some policy and decision-makers may not be convinced of the need for immediate action, while others may be willing to act on a precautionary basis. Within the EU, WW is regulated under the Urban Waste Water Treatment Directive which requires that all member states ensure water collection and treatment for communities with populations larger than 2000 people. The Directive establishes principles for the design, construction and treatment of plants and systems, as well as minimum standards for the water treated (European Environment Agency, 2018; SAM, 2018). While there have been discussions on altering the directive to accommodate MPs, this has not been done (Clayton, 2016).

This means that mechanisms for transmitting high-level policy initiatives into operation are weak. Innovation in this field will occur only if the investors and WWTP operators believe that research and development, implementation (including new infrastructure) and operations will be cost effective in the long run. Most utilities are not market driven and therefore regulation must be constructed in a manner that incentivizes investment in new infrastructures and practices (Beecher, 2013; Porter and Van der Linde, 1995). According to industry experts, the conservative nature of the WWT industry, tough financial markets and current regulatory structures in many places means that it can take a minimum of five years to deploy a new technology (Gale, 2014; Rehan et al., 2011). This type of time lag can be an added deterrent to research and development because it creates uncertainties about whether new technologies will reach the market. Environmental regulation coupled with innovation subsidies have been shown to incentivize investment and may provide an effective mechanism because they can simultaneously provide clear standards to guide operations with support for targeted, industry-oriented research aimed at refining the technologies needed to comply with regulation (Xu, 2016).

With respect to the research and development stages of the innovation chain, the approach used in the *GoJelly* project shows promise by building on a prior proof of concept for using a bio-based filter instead of mechanical and chemical processes that have proven to be ineffective or too costly. The teaming of marine ecologists, jellyfish experts, microplastics and WW specialists has proven to be an essential element in progressing from experimental stages to piloting the filter. The interdisciplinary team that draws on these separate research fields has enabled us to map out the steps needed for the chain of production and deployment of the bio-based filter, from the capture of jellyfish through to the methods of deployment within a WWTP.

Policy and regulatory opportunities intersect with the age profile of plants and equipment in the WWT sector. While MP retention rates above 90% can be achieved by plants operating with tertiary treatment, in Europe WWTP operations are quite variable and rates can be as low as 53% if technology is outdated and only primary and secondary treatments are conducted, as is the case in many older plants (Hann et al., 2018). Much of the European and North American infrastructure was built during or before the 1970s and will need to be replaced or refitted in the next ten years. This presents an opportunity to deploy more up-to-date technologies capable of complying with changed regulations requiring the removal of MPs. WWTP operators are increasingly aware of the issue of MPs and within the scientific literature a number of recent articles have addressed the challenge of MPs for the WWT industry (Canadian Water Network, 2018; Drew, 2017; Huber Technology, 2019). Improved removal of MPs in WW may also confer additional benefits. At least one study observed that MPs and NPs in WW clog certain mechanical processes within WWTPs and more efficient systems may translate into lower maintenance costs for operators (Enfrin et al., 2019). If bio-based filters prove to require less investment in infrastructure than other options, deployment, even within current WWT systems, could be technologically and economically feasible.

6. Conclusion

WWTPs already capture a sizeable proportion of MP particles from WW but owing to the large volumes of WW processed within these plants, treated WW still makes a sizeable contribution to aquatic MP pollution. Moreover, the particles released in treated WW tend to be smaller and contain a high proportion of fibers, which may pose hazards to planktonic species and live stages at the base of aquatic food webs in ways that larger particles do not. While part of the solution to the challenge of stemming the flow of MP particles reaching surface waters must surely rest with WWTPs, there are currently no cost-effective technologies for capturing very small and fiber-shaped MPs. However, several systems currently being developed show promise. Diverting MP particles from WWTP influents into the sludge phase creates the need for additional innovation in the treatment process since the sludge subsequently represents a source of MP pollution. Although this paper does not deal directly with management of MPs at this stage of WWT, we note that this must be a consideration if WWTPs are to be effective in managing MPs.

The cost and effort of developing such mitigation systems can only be justified if there is a reasonable expectation that they will be adopted by the WWT sector, which would require changes to policies and regulations governing the operation of WWTPs. Such changes may include new standards for MP levels in WWTP effluents, as well as measures to ensure that the cost of deploying new systems can be recouped by plant operators. However, any policy or regulatory changes need to be based upon an acceptable level of proof that MPs pose a risk to ecosystems at environmentally relevant concentrations and therefore justify the need for such mitigation actions. As a result, the partnership between applied scientific researchers, industry stakeholders and water policy decision makers is key to making the WWT sector a key player in meeting the challenge of reducing MP emissions to the environment. Finally, emphasis must be given to the fact that improved WWT is one part of what must be a multi-faceted approach to solving the problem of marine MP pollution and wider environmental MP pollution. Any efforts must form part of a broader approach that addresses the need for reducing plastic consumption, reducing the levels of uncontrolled plastic release, reducing the quantity of disposed plastics waste and better management of plastic waste through improved recycling and circular economy approaches.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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