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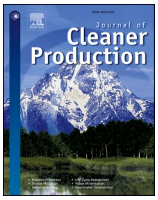

Review

The role of different sustainable urban drainage systems in removing microplastics from urban runoff: A review

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ABSTRACT

Urban runoff is considered an important source of microplastic pollution. This review provides an in-depth analysis of studies that assess the role of sustainable urban drainage systems (SUDS) as nature-based solutions, to tackle this worldwide problem. Sedimentation-based systems, such as wetlands or ponds, and filtration-based systems, such as bioretention cells or gardens, as well as permeable pavements have been shown to effectively retain a significant number of MPs. Nevertheless, it is considered that efficiencies can be enhanced through some design improvements, proposed in this review. Polypropylene, Polyethylene terephthalate, Polyethylene and Polystyrene, are the most frequent and abundant polymers in urban runoff, due to high consumption in a wide variety of urban products and activities. Smaller particles and fibers are the most challenging fraction. Maximum rainfall intensity, antecedent dry days, rainfall depth, land use, dwelling density, imperviousness, hydraulic loading, SUDS age, and the presence of forebays or gross pollutant traps have been influential variables on the abundance of MPs in some of the studies, although not always statistically significant. The assessment of the fate of MPs by some studies indicates that they are more concentrated in the sediment or filter media near the inlet, as well as in the shallower layers. The existence of a similar behaviour and a correlation between total suspended solids and microplastic concentration, makes them a potential indicator of microplastic pollution. A wide variability of microplastic detection methods and reporting data format has been found, which makes it difficult to draw global conclusions. Measures to reduce microplastic pollution in urban areas and subjects for further research are finally suggested.

1. Introduction

Scientific literature defines microplastics (MPs) as plastic particles whose longest dimension is below 5 mm (Malankowska et al., 2021). In the first International Research Workshop on the Occurrence, Effects and Fate of Microplastic Marine Debris, MPs origin was defined according to primary and secondary sources. Primary MPs consists of manufactured particles for a specific use or purpose, whereas secondary MPs are plastics which have suffered breakdown processes in the environment (Arthur et al., 2008).

Widely present in the environment, MPs cause threats to the environment and humans, and contribute significantly of the deterioration of natural resources and wildlife (Grbić et al., 2020; Müller et al., 2020; Sun et al., 2019; Zhang, 2017). There are several modes of harm, depending on the size of plastic specks (Lim, 2021). When plastics are small enough (nanoplastics), they can enter cells or tissues, which might cause irritation or inflammation of lung tissue and lead to cancer, or deposit in the airways and lungs, provoking respiratory damages, among others. Larger microplastics are more likely to cause negative effects due to chemical toxicity, because they may contain plasticizers, stabilizers and pigments, many of which are hazardous. They can also adsorb toxic substances and act as carriers or cause malnutrition and starvation through satiation by ingesting particles with no nutritional value (Lim, 2021).

These small particles can be found in the atmosphere, soil, sediment, freshwater bodies and oceans (Ziajahromi et al., 2020). Focusing on freshwater, the main sources and paths of MPs to reach these water bodies come from the urban environment. Human's activities related to industry, household laundry, construction, tire wear, street furniture wear, leakages from urban waste collection systems, among others lead

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to wastewater treatment plant (WWTP) effluents and stormwater runoff contamination (Koutnik et al., 2021; Qiu et al., 2020).

Great proportion of the MPs removed at WWTPs are transferred into the sludge, whereas others are released to the environment (Liu et al., 2021). This poses an environmental risk because sewage sludge is frequently applied in croplands and hence represents a major input to the environment (Hernández-Arenas et al., 2021). The efficiency of big WWTPs at MP removal is thus a cutting-edge research topic. Many studies on the different techniques used for collecting MPs, their pre-treatment and characterization methods, have been issued (Sun et al., 2019). Further, in recent years, it has been noticed a major concern on studying WWTPs in small communities. These treatment plants are often based on or complemented with constructed wetlands that provide tertiary treatment (Wang et al., 2020).

In wet weather, stormwater runoff and combined sewage overflows (CSOs), transport important loads of pollutants, reaching water bodies without previous treatment (Piñon-Colin et al., 2020). Indeed, some studies have found a higher MP abundance in rainy seasons or after a rain event, in river, estuarine or seawater (Cheung et al., 2019; Jiang et al., 2022). Cheung et al. (2019) showed that plastic abundance dropped over ten times (14.0–1.3 pieces/m^3) within 2 h after a rainfall event in Lam Tsuen River. Zheng et al. (2020) measured a significantly higher quantity of MPs in Bohai Sea zooplankton community in the rainy season than that in dry season. These findings suggest that diffuse pollution during rainfall events may be a major MP pollution pathway. Nonetheless, there is a limited number of studies focused on the removal of MPs from urban stormwater runoff.

MP pollution control requires a combination of multiple and varied actions, including legislation to regulate the production of single use plastics or banning the addition of microbeads in personal care products, improving policies of plastic waste management, strengthen the recycling and utilization of plastic waste (Zhong and Li, 2020; Directive (EU) 2019/904), developing technologies to prevent and collect marine plastic pollution, such as laundry balls or water filters on laundry machines or stormwater and wastewater filters (Schmaltz et al., 2020). Even if waste management was improved significantly, there are many plastic-made elements in urban areas that can release MPs in rain events (street furniture, pipes, car pieces, etc.). For preventing the discharge of MPs from urban runoff, sustainable urban drainage systems (SUDS) can be part of the solution (Monira et al., 2021).

SUDS are engineered nature-based solutions for sustainable urban stormwater management, that provide water quality improvement and prevent from diffuse pollution. SUDS aim at mimicking and restoring hydrological processes existing prior to urban development (infiltration, filtration, storage, evapotranspiration, etc.), by integrating runoff management devices into the urban landscape (Andrés-Doménech et al., 2021). There is a wide variety of SUDS, including permeable pavements, filter strips, vegetated swales, infiltration trenches, soakaways, rain gardens, detention and retention basins, detention and retention ponds, and constructed wetlands, among others (Woods-Ballard et al., 2015).

This review aims to compile and analyse the results obtained in previous studies in which the capacity of various types of SUDS to retain and remove MPs from urban runoff has been evaluated. The distribution of the MPs within the systems, and the influence of their size, shape or composition is also analysed. The ultimate goal is to identify possibilities for design improvements, as well as aspects that remain to be studied.

2. Methodology

2.1. Literature search

An exhaustive searching process of a wide variety of keywords, using different scientific and academic engines, has been carried out (Table 1). The databases were accessed on September 6, 2021 for the first time and reviewed every two weeks since then. No time limit of publication date was defined. A first search roughly checked existing studies related to microplastics in stormwater runoff, combining keywords such as "stormwater", "runoff", "urban", "surface", "microplastics" and "retention", obtaining a large number of results.

From the analysis of these results, a second search (A) used the combination of the terms "microplastics" as term 1, and "stormwater runoff" or "runoff" or "surface runoff" or "urban runoff" as terms 2. It was noticed that the papers found according to this search, were closer to the interest of this investigation.

Then, to slightly narrow the search and to select proper papers, a more refined search was done (B), incorporating a complementary term. Term 3 aims at encompassing terminology that describes MP retention techniques, as it varies according to its location of application. For example, the term SUDS is used in the UK; Water Sensitive Urban Design (WSUD) in Australia; Best Management Practices (BMPs) in North America; Low Impact Development (LID) in North America and New Zealand, and Sponge Cities in China. Other recent globally adopted terms, are Green Infrastructure (GI) and Nature-Based Solutions (NBS) (Qi et al., 2020). Additionally, to strengthen the literature search, citations to the papers selected from search B and its own bibliography, were tracked.

2.2. Selection criteria and results of the search

Eligible studies focus on whether stormwater runoff and microplastics have been managed by any SUDS technique, and provide relevant information, such as treatment capacity efficiency, or microplastic identification methods used, among others. Only articles and review articles published in the English language were examined, excluding index documents.

As a result, a total of 23 studies met the requirements and were selected for this review. The studies were geographically located in Europe (n = 10), North America (n = 6), Oceania (n = 6) and Asia (n = 1). It is important to emphasise the significantly reduced number of publications on this research line.

Table 1
Summary of searches, terms and results from the considered search engines.

						Results		
Search id	Term 1	Boolean operator	Term 2	Boolean operator	Term 3	Web of Science	Science Direct	Google Scholar
A	Microplastics	AND	Runoff	–	–	252	2041	8770
		OR	Stormwater runoff					
			Urban runoff					
			Surface runoff					
B	Microplastics	AND	Runoff	AND	NBS	10	104	1120
			Stormwater runoff		SUDS	10	42	278
			Urban runoff		Sponge cities	10	35	267
		OR	Surface runoff		LID	10	36	277
				OR	BMPs			
					GI			
					WSUD			

3. SUDS experiences for MP management

Covering available literature, fewer SUDS techniques for MP management have been identified, in comparison to all available solutions. Specifically, five different SUDS types have been studied under diverse land use conditions. A brief description of these SUDS is included in the Supplementary Information. These techniques consist of urban wetlands (in 4 studies), including urban park water bodies (UPWB, in 1 paper); stormwater detention ponds and basins (SWP, in 7 papers); bioretention structures (BS, in 7 papers), that comprise rain gardens, biofilters, bioretention cells and bioretention basins; sand filter (SF, in 4 papers); and permeable pavements (PP, in 1 paper).

The research developed by Su et al. (2019) within the Greater Melbourne Area in Australia, monitored microplastic presence in nine urban stormwater wetlands, that intercept and treat stormwater from intensive commercial and industrial activities. Townsend et al. (2019) examined microplastic pollution in 20 urban wetlands, also in the Greater Melbourne Region. These water bodies receive water from stormwater runoff, produced at commercial, industrial, open space (undeveloped), residential, road/rail, rural, semi-rural and urban growth land uses. Also in Melbourne, Pramanik et al. (2020) collected stormwater road runoff samples from a constructed wetland. A research developed by Ziajahromi et al. (2020), aims to measure concentrations of MPs at inlet and outlet of a stormwater floating treatment wetland, located at the Gold Coast, Australia. Yu et al. (2021), investigated MP pollution in 12 UPWB in Xi'an (China), according to different specific locations and land uses, such as industrial, tourism, commercial and residential. Although the UPWB were not specifically implemented to manage urban runoff, they have been considered in this review as they receive stormwater runoff. More recently in Gdansk (Poland), a multistage constructed wetland system was preliminary studied by Jakubowicz et al. (2022) to detect and remove pollutants from a stormwater collector, in a highly urbanised catchment of 1740 ha (Vahvaselkä et al., 2022).

Besides, Coalition Clean Baltic (2017) summarizes the study carried out by Jönsson (2016). In this case, MPs are managed by two stormwater ponds in Sweden. Klöckner et al. (2019) studied a determination method of tire and road wear particles (TRWP) and obtained concentrations of these particles in two road and highway runoff treatment facilities in Halensee and Leipzig, Germany. The treatment systems consisted of a sedimentation basin (SB) and a soil retention filter (SRF) and two consecutive settling ponds (SP). Liu et al. (2019a, b) analysed MP concentrations in both water and sediment matrix of seven retention ponds in Denmark, from residential, industrial, commercial and highway landscapes. A study carried out by Olesen et al. (2019), analyses the presence of MPs in a stormwater retention pond located in the Danish city of Viborg. A total area of 166 ha (70 ha impervious) drains to the stormwater pond, which surface area is 6690 m^2 and approximately 7500 m^3 its total volume. The catchment land use is defined as light industry, including production industries, retailers, building supply stores, parking lots, and roads with semi-heavy traffic. Pramanik et al. (2020) studied road dust as a potential source of MPs in a stormwater pond. Laplaca and van den Hurk (2022) characterized MP abundance found in aquatic biota from 3 stormwater ponds and 4 adjacent tidal creeks in South Carolina (USA). These SWPs receive stormwater from drainage areas with different land uses, such as residential, commercial, highway and golf course.

Recently, Lange et al. (2023) investigated the abundance and distribution of microplastics in nine 7-12 year-old BS, looking at different depths of the filter media and distance from the inlet. The BS were located adjacent to roads or parking lots in urban areas classified as industrial, commercial, downtown ultra-urban, or mixed residential and commercial, which catchment areas to the BS ranged from 50 m^2 to 318, 500 m^2. Koutnik et al. (2022a, b) focused their investigations on filtration-based BS. In the first study, the authors analysed atmospheric deposition of MPs, together with spatial distributions above and below ground of 14 structures in Los Angeles, USA. These BS manage stormwater from driveways and parking lots, residential and commercial areas with low and medium traffic streets, high traffic areas, and a natural area. Within the second study, 2 biofilter models (sand-based and soil-based) at laboratory scale were simulated, and evaluated the remobilization effect of loaded MPs, after subjecting the biofilters to dry-wet or freeze-thaw cycles. Mbachu et al. (2022) studied MPs and meso-plastics accumulation in 20 BS in suburban residential areas. Werbowski et al. (2021) support the study conducted by Gilbreath et al. (2019), which aims at assessing the efficiency of a rain garden for pollutant removal, including MPs. The BS is filled with engineered soil mix and manages a drainage area of 4080 m^2 in California, USA. The catchment, mostly impervious, includes medium-density residential, commercial and road land uses. A more recent study, characterizes and quantifies MPs in urban stormwater runoff through a bioretention cell (Smyth et al., 2021). In this case, the study site located in Ontario (Canada), receives stormwater runoff from an impervious parking lot with a 265 m^2 drainage area. Boni et al. (2022), determined MP presence in a bioretention basin that receives stormwater from an adjacent parking lot, road, and academic buildings in New Jersey, USA.

Lange et al. (2021, 2022) studied a stormwater treatment train located in Sundsvall, Sweden. The treatment train is composed of a gross pollutant trap (GPT) connected to either a subsequent vertical flow BS or a non-vegetated SF system. The system manages runoff from a total impervious catchment of 4.7 ha including motorway use. Another SF system was studied by Pankkonen (2020) to compare two fine filtration media (sand and biochar) for stormwater filtration in Helsinki, Finland. The SF system is placed in a separate stormwater sewer, to manage runoff generated in a 53 ha catchment with intense traffic, before entering a seawater bay.

The study developed by Rasmussen et al. (2023) concerned the analysis of sediment dust accumulated on seven PP roads and parking lots, used for residential, industrial, and commercial purposes. The sampling sites were located on the peninsula of Jutland and the island of Funen in Denmark.

4. Microplastic detection techniques

4.1. Sample matrix

The sample matrix represents the medium where samples are taken and needs to be defined according to the objectives of the research. Three different matrices have been detected from the considered studies: water, sediment and fauna.

Water and sediment are the most sampled mediums. Boni et al. (2022); Coalition Clean Baltic 2017 (2017); Gilbreath et al. (2019); Jakubowicz et al. (2022), Lange et al. (2021, 2022); Liu et al. (2019a); Pankkonen (2020), Pramanik et al. (2020) and Smyth et al. (2021), exclusively focused their analysis on this matrix. Concretely, samples were taken from inlets (IN) and outlets (OUT), and/or inside the water column (IWC). In relation to the sediment, Lange et al. (2023), Rasmussen et al. (2023), Koutnik et al. (2022a, b), Mbachu et al. (2022), Liu et al. (2019b), Klöckner et al. (2019) and Townsend et al. (2019) analysed this medium, while Yu et al. (2021) and Ziajahromi et al. (2020) studied both water and sediment matrices. Fauna is the least studied matrix within the revised studies. Su et al. (2019) monitored MPs in fish and amphibian species from stormwater wetlands, whereas Laplaca and van den Hurk (2022), studied the presence of MPs in fish and invertebrates. Only the study developed by Olesen et al. (2019) addressed the identification of MPs in the three matrices, showing the importance of this holistic approach. When the three matrices are evaluated, it is possible to know whether there is an accumulation of MPs in any of them, in comparison to the others.

4.2. Sample collection

The sample collection process can be conducted in different ways.

Parameters such as number and volume of samples, or mesh sizes, widely varies depending on the authors, even when the same sampling matrix is considered.

Meteorological conditions and available resources, determine the number and volume of samples to process. Depending on the medium where MPs are analysed, samples are measured as volume (at water and sediment matrices), mass (at sediment matrix), and as a number in fauna. According to the sample matrix, Tables 2–4 show and describe characteristics and particularities of the samples taken according to the literature for the different matrices.

From the consulted references, a total of 21 different sieve sizes have been identified. Table 5 shows references which provide mesh size information, and fraction limits defined by the authors. Whenever possible, it is recommendable to use 10 or 20 µm as minimum size

Table 2
Detailed information of samples characteristics in water, including number of samples taken, sampled volumes and a short description of the procedure.

Reference	No. of samples	Total sampled volume	Additional information
Boni et al. (2022)	3	15 L	Samples taken from 3 separate events, considering 1 to 18 antecedent dry days. Every sample (5 L) consists of the composition of 1 L collected 20–40 min apart during the storm.
Coalition Clean Baltic (2017)	Non-defined	Non-defined	Non-defined
Gilbreath et al. (2019)	6	20–40 L	Samples taken from 3 storm events and collected at inlet and outlet points.
Jakubowicz et al. (2022)	4	Non-defined	Two samples taken before treatment, and 2 samples after the treatment process.
Lange et al. (2021, 2022)	48	1.8–20 L	Composed water samples were taken during 9 rain events, at 5 points (inflow, GPT outflow, filter inflow, bioretention cell outflow and sand filter outflow). 3 additional samples were taken from the surface water (0–5 cm) of the sedimentation compartment from 3 specific events.
Liu et al. (2019a)	21	6742 L	The sampling campaign consisted of 3 rounds during dry weather, with a minimum of 2 weeks between samplings.
Olesen et al. (2019)	5	50 L	Water sampled 5 times during dry weather. At least 14 days between samplings. Every sample consisted of 10 L of pond water.
Pankkonen (2020)	6	Non-defined	Influent and effluent water samples taken from 3 rain events.
Pramanik et al. (2020)	Non-defined	Non-defined	Samples taken during rain events from different points in the stormwater pond inlet; and from inlet and outlet of the constructed wetland.
Smyth et al. (2021)	19	9.5–38 L (0.5–2 L per sample)	A total of 19 runoff events were sampled at inlet and outlet points.
Yu et al. (2021)	36	360 L	3 different samples collected from different points in each water body. Each sample was a composite of multiple parallel sub-samples.
Ziajahromi et al. (2020)	6	Non-defined	Samples collected at inlet and outlet points with 2 replicates, after a heavy rain event (34 mm/d).

Table 3
Detailed information of samples characteristics in sediment, including number of samples taken, sampled volumes or mass, and a short description of the procedure.

Reference	No. of samples	Total sampled volume or mass	Additional information
Lange et al. (2023)	33	Non-defined	Samples from 9 BS located at 1 and 3 m from the inlet (locations 1 and 2). At location 1, 2 samples were taken at 0–5 cm and 10–15 cm depth of the filter media. At location 2, samples were taken at 0–5 cm of the filter media.
Liu et al. (2019b)	>7	≥21 L (≥3 L of sediment from each pond)	Sediments sampled during dry weather with antecedent dry weather period of more than 2 days. Samples were taken at 1 m water depth, collecting the top 5 cm of the sediment. For each pond, samples were collected the same day from three randomly locations and were combined as one sample.
Mbachu et al. (2022)	60	Non-defined	The sampling period took place for 3 months. Soil samples were taken from 0 to 400 mm depth at each system. Three sampling locations were selected for each site (inlet, middle and outlet).
Klöckner et al. (2019)	5	5 g (1 g of sediment from each environmental samples)	Particulate samples from 2 road/highway runoff treatment facilities. 1 sample was conducted at the SB, and 2 samples at the SRF. Other 2 samples were taken from the 2 SPs.
Koutnik et al. (2022a)	140	Non-defined	Soil samples collected after a two months dry period, and at 10 cm depth.
Koutnik et al. (2022b)	26	26 g	A total of 14 and 12 samples of the filter media for sand-based BS and soil-based BS respectively. Half of the samples correspond to dry-wet and freeze-thaw cycles.
Olesen et al. (2019)	1	1–2 kg	Sediments were collected approximately midways between the inlet and outlet of the pond, from the top 5–8 cm of sediment layer.
Rasmussen et al. (2023)	Non-defined	750 kg	Road dust was collected from seven sites. Total sampled road area was 5300 m^2 and approximately 100 kg of particulate material was sampled per site.
Townsend et al. (2019)	20	10 L	Composed sample of 500 mL of superficial sediment, taken from inlet, middle and outlet of every wetland.
Yu et al. (2021)	36	60 kg	A total of 5 kg of surface sediment (0–6 cm) was collected at the same sampling points and sites of the water samples.
Ziajahromi et al. (2020)	6	6 kg (1 kg wet weight from each sampling point)	Samples taken from the top 5 cm of the bottom sediment at the inlet and outlet, considering 2 replicates.

Table 4
Detailed information of samples characteristics in fauna, including number of samples taken, sampled species, and a short description of the procedure.

Reference	No. of samples	Specie(s)	Additional information
Laplaca and van den Hurk (2022)	118	*Micropterus salmoides, Gambusia holbrooki, Menidia menidia, Lepomis* spp.	Information referred only to the stormwater ponds.
Olesen et al. (2019)	Non-defined	*Gasterosteus aculeatus* *Triturus vulgaris*	Fish and newts were sampled in quantities suitable for further analysis. The fish caught were 2–6 cm long (average of 4.8 cm and 6.38 g of wet weight). The newts were 5–7 cm long with an (average of 5.9 cm and 4.61 g of wet weight.
Su et al. (2019)	180	*Gambusia holbrooki*	Fish individuals caught from nine wetlands, and collected from an approximate depth of 200–500 mm.

Table 5
Sieves used in revised literature.

Reference	Sieve
Boni et al. (2022)	250 μm–500 μm – 2 mm
Coalition Clean Baltic (2017)	20 μm–300 μm
Gilbreath et al. (2019)	125 μm–355 μm – 500 μm–1 mm
Klöckner et al. (2019)	500 μm
Koutnik et al. (2022a)	2 mm
Lange et al. (2021)	100 μm–300 μm
Lange et al. (2022)	20 μm–100 μm
Lange et al. (2023)	40 μm–5000 μm
Laplaca and van den Hurk (2022)	53 μm–500 μm
Liu et al. (2019a, b)	10 μm–500 μm – 2 mm
Mbachu et al. (2022)	300 μm–4 mm
Olesen et al. (2019)	10 μm–80 μm – 500 μm
Pankkonen (2020)	90 μm–300 μm – 1 mm
Smyth et al. (2021)	106 μm–300 μm – 500 μm–1 mm
Townsend et al. (2019)	35 μm–1 mm
Yu et al. (2021)	75 μm for water samples
Ziajahromi et al. (2020)	25 μm–100 μm – 190 μm–500 μm

because of the high abundance of particles ranging in size from 10 or 20 to 100 μm, according to the reviewed studies, and as discussed later in section 5.3.

At this stage, it is noteworthy that a proper sampling of urban runoff should cover as much rainfall events as possible, in order to estimate the total quantity of pollutant that enters and leaves the SUDS structure. At least the first flush, when pollutants are usually more concentrated, should be covered. This task is commonly addressed by using autosamplers programmed according to the typical rain pattern of the area to be characterised (Andrés-Doménech et al., 2018; Perales-Momparler et al., 2014 and Sansalone and Cristina, 2004).

4.3. Sample processing method

Once the sample is sieved and particles are recovered, it is highly desirable to process it in order to facilitate identification and characterization of MPs. Shruti et al. (2021) produced a very illustrative diagram concerning the stages for sample conditioning. A first step is the digestion of the material recovered from the sieves to remove organic matter and open up the matrix. Several digestion procedures have been used in the reviewed studies: H_2O_2 (9 studies), Fenton's reagent (4 studies), enzymatic (1 study), combination of enzymatic and Fenton digestion (4 studies), microwave assisted nitric acid digestion (1 study which used Zn as marker), Sodium Dodecyl Sulfate (1 study), KOH (2 studies), NaOH (1 study) or none (6 studies). In general, H_2O_2, Fenton's and enzymatic digestions, and combinations thereof, are used for water and sediment samples, while alkaline solutions are employed for fauna.

A second step is density separation, in which salt concentrated solutions are used for this purpose. The solutions, and their density, utilized in the reviewed studies were: $ZnCl_2$ (1.5–1.97 g/mL, 5 studies), $CaCl_2$ (1.4 g/mL, 2 studies), NaI (1.59–1.85 g/mL, 2 studies), NaCl (1.2 g/mL, 1 study), mixed salt solution (unknown, 1 study), sodium polytungstate (1.9 g/mL, 1 study), and KI solution (1.68 g/mL, 2 studies). Shruti et al. (2021) recommended the following workflow: sieving – digestion (H_2O_2, 60 °C) – density separation (NaI or $ZnCl_2$) – Fenton's/Enzymatic digestion – filtration. The higher density of $ZnCl_2$ provided better recovery results than NaCl, especially for acrylic, Polyvinyl Chloride and Polyethylene terephthalate (Townsend et al., 2019). However, these recommended denser solutions are discarded by some authors for reasons of toxicity or price, as they are more expensive than common salt or calcium chloride. An alternative to enhance the performance of NaCl or $CaCl_2$ is the addition of $NaHCO_3$, heating and stirring the solution, to facilitate the release of CO_2 bubbles and promote the flotation of denser MPs (Hernández-Arenas et al., 2021).

4.4. Microplastic identification methods

Microplastics identification represent a difficult task in their analysis due to the existence of a wide variety of sizes, shapes, and polymers. Therefore, the MP identification process commonly combines different analytical techniques, based on physical characterization (for example visual identification or microscopy), and chemical characterization, such as spectroscopy (Shim et al., 2017).

Looking at chemical identification procedures, Fourier transform infrared (FTIR) spectroscopy is the most used method (14 studies). It has been noticed that FTIR method is complemented with additional modes when small or irregular microplastics need to be detected. In these cases, authors use both micro-FTIR (μFTIR) to perform microscopic observation of MPs; and attenuated total reflectance (ATR-FTIR) to produce stable spectra from irregular microplastic surfaces. Also, semi-automatic mapping techniques are usually applied to FTIR method. The focal plane array (FPA)-based reflectance imaging method identifies microplastics on larger surface areas and allows reduction of manual effort in the FTIR process (Shim et al., 2017). In some cases, different methods are combined with the objective to cover wider microplastic size ranges and origins in the identification process. Raman spectroscopy is also used (3 studies), particularly convenient for small particles (<1 μm), as it shows better spatial resolution (Sun et al., 2019).

Only 3 studies considered the use of stereo or dissecting microscope for MP identification. Other less common techniques are the selection and quantification of markers. For instance, Klöckner et al. (2019) developed a procedure based on Zn determination after density separation, or thermal extraction desorption gas chromatography-mass spectrometry (TED-GC-MS) (Eisentraut et al., 2018). The methodology is considered a fast process that simultaneously can analyse thermoplastics and tire wear particles, although it cannot provide particle information (number, size, or shape). Koutnik et al. (2022a, b) used an UV–Vis spectrophotometer after colouring MPs with Nile Red in chloroform solution. This method has limitations, as it does not differentiate between types of polymers, and tire particles might not be detected if they do not absorb Nile Red. Another technique to be mentioned, despite it is not used in the reviewed papers, is the scanning electron microscope (SEM), which allows to characterise particles surface and to detect signs of degradation (Chen et al., 2021), so it could evaluate whether physicochemical and biological degradation processes are affecting to retained MPs in SUDS infrastructures.

Some authors have faced the challenge of evaluating tire wear particle content. Despite meeting the International Organization for Standardization's (ISO) description of plastic, elastomers are not considered plastics in ISO's definition because of their reversible elastic deformation (Hüffer et al., 2019). Nevertheless, as they represent a major pollution problem, representing around 60% of MP emissions when considered as MPs, and have synthetic polymers in their composition (Eisentraut et al., 2018), it is desirable to assess them when characterizing urban runoff. However, the identification of tire wear particles is a challenging task. Carbon black, used as a reinforcing filler in tires, absorbs light throughout the infrared region, thus hindering the acquisition of transmission or reflection spectra by FTIR (Liu et al. 2019a, 2019b). For this reason, these authors could not identify car tire rubber in water or sediments. Other identified issues for spectroscopy methods (Raman, FTIR) are the emission of fluorescence, particle burning, uninterpretable spectra, or variability in tire composition, which can include natural rubbers and a host of fillers and property enhancing agents (Eisentraut et al., 2018; Smyth et al., 2021; Werbowski et al., 2021). Smyth et al., 2021 used μFTIR after applying a baseline correction to spectra, as needed. Even so, they could not confirm the chemical composition of rubbery particles. Laplaca and van den Hurk (2022) classified as suspected tire wear particles, those that met certain criteria of colour, shape, texture, flexibility and state of cleanliness.

However, some authors could identify tire and road wear particles (TRWP) using Raman or FTIR techniques (Lange et al., 2023; Grbić et al., 2020; Moruzzi et al., 2020). Two particles were identified as Vine Black or carbon with Raman, and others as Ethylene Propylene Diene Monomer rubber (EPDM rubber) and Ethylene-Vinyl Acetate (EVA) rubber using μFTIR and ATR-FTIR (Grbić et al., 2020; Lange et al., 2023). They assumed that non-identifiable particles came from tires based on their rubber-like texture and elongated shape. Klöckner et al. (2019) developed a method based on the selection of Zn as a marker element of TRWP, consisting of density separation and Zn determination, suitable for samples from high traffic density environments. Eisentraut et al. (2018) simultaneously measured microparticles derived from thermoplastics and tire wear using thermal extraction desorption gas chromatography-mass spectrometry (TED-GC-MS) and selecting decomposition compounds as markers.

4.5. *Quality assurance and quality control methods*

Quality assurance and quality control usually include measures to minimize and quantify potential contamination, replication of samples and recovery assays to check the performance of the methods used. The main actions to prevent artificial contamination consist of thoroughly rinsing of all materials and equipment, avoiding plastic as much as possible, using cotton lab coats and nitrile gloves, cover filters and samples with aluminium foil and avoid air flows (Shruti et al., 2021). Commonly implemented measures to assess background contamination include the processing of a given volume of deionised water as if it were a sample, covering all steps of both sampling and laboratory treatment (usually referred to as field blanks). Some authors run a second type of blanks including only the steps carried out in laboratory (lab blanks) (Lange et al., 2021). Additionally, it is also advisable to expose wet filters to air during microscopic examination of samples (Lange et al., 2021). The analysis of particles scraped from the equipment used for sampling, or from the SUDS infrastructures, is useful to assess contamination from these potential sources (Ziajahromi et al., 2020; Lange et al., 2021). Finally, recovery assays consist of spiking some clean samples, or samples of known concentration, and analyse them to assess what percentage of the spiked particles is detected. It is advisable to include a variety of polymers, sizes and shapes to be as representative as possible (Townsend et al., 2019; Olesen et al., 2019; Smyth et al., 2021).

5. Occurrence and fate of MPs in SUDS

5.1. *Background contamination*

Data concerning the background contamination shows high variability, both in the procedure and in the way the results of blanks are reported, as well as in the magnitude of the values measured by the different authors. Several studies reported the blank results in terms of concentration (Olesen et al., 2019; Liu et al. 2019a, 2019b; Smyth et al., 2021; Lange et al., 2022; Boni et al., 2022).

For water, the values varied between 0 and 89 items/L. The minimum value of no particles was found by Boni et al. (2022), who highlighted that it could be related to the fact that they did not target either fibers, particles of size lower than 250 μm, nor non-buoyant MPs because they used NaCl 1.2 g/mL. Ziajahromi et al. (2020) and Werbowski et al. (2021) reported the values in terms of items, obtaining 7 and 13 items in field blanks and 4 and 2 items in laboratory blanks, respectively. Others do not give information about background contamination. Ziajahromi et al. (2020) checked the composition of blank items by FTIR, concluding that they were not plastic. Smyth et al. (2021) did not confirm the lab blank particles as plastic either. In general, fibers accounted for a significant part of blanks items: around 60% (Werbowski et al., 2021), 95% (Smyth et al., 2021) or 25% (Liu et al., 2019a; Olesen et al., 2019).

For sediments, only Liu et al. (2019) and Olesen et al. (2019) reported blank contamination, obtaining largely different values, 108 and 5000 items/kg respectively (Fig. 2).

For fauna, Su et al. (2019) obtained a mean level of background concentration of 0.033 items/g or 0.067 items/ind. and a detection rate of 6.67%. Laplaca and van den Hurk (2022) considered 10 procedural blanks, containing an average of 1.1 ± 0.6 MP per blank. In these 2 studies all the results were corrected by subtracting this mean value. In contrast, Olesen et al. (2019) found a concentration several orders of magnitude larger, $5\cdot10^4$ item/kg.

Most studies did not correct the sample results, i.e., they did not subtract the values obtained in the blanks. The main reason is the uncertainty on whether all samples were equally contaminated. Blank concentration can be considered as limit of detection instead (Smyth et al., 2021; Miller et al., 2021). In general, none or small contamination from the sampling instrumental was found (Liu et al. 2019; Lange et al., 2021). Contamination presumably came from the equipment and surrounding air and not from the water used (Liu et al. 2019). Indeed, atmospheric deposition is a significant source of MPs in urban areas (Koutnik et al., 2022a).

5.2. *Microplastics abundance in SUDS*

The information gathered from the reviewed studies is shown in Fig. 1 (water matrix) and Fig. 2 (sediment matrix). The box-and-whisker plot in Fig. 1, indicates a high variability of microplastic concentration **in water**, ranging from less than 1 to 4250 items/L in the inlet of SUDS, and between 0.16 and 335.48 items/L in the outlet or inside the system. Most descriptive statistics (min, mean, median, Q3, max and outliers) decrease from the inlet to the outlet, so it is right to conclude that SUDS develop a significant role in MP pollution control. Indeed, outlet or inside system values, were in the same order of magnitude as background concentration. Studies related to stormwater ponds or wetlands did not analyse inlet and outlet sites, apart from Ziajahromi et al. (2020) and Coalition Clean Baltic 2017 (2017). The former, who sampled after a heavy rain event (34 mm/d), found higher concentration (4.0 ± 2.4 items/L) in the outflow than in the inflow (0.9 ± 0.3 items/L), while the latter obtained a decrease in concentration from the inlet (1000–4250 items/L) to the outlet (100-50 items/L) in two stormwater ponds. Higher concentrations in outflows than in inflows, could be related to the first flush effect, as the authors discussed, highlighting the risk of mobilization of MPs previously settled in pond sediments. Nevertheless, it is worth noting that actual pond efficiency should be calculated in terms of load reduction, as in general, these stormwater management systems dampen down both the flow rate and the concentration. In case of BS, abundance of MPs shows a clear decrease from inlet to outlet (Fig. 1). Lange et al. (2022) obtained a reduction in particle concentrations from

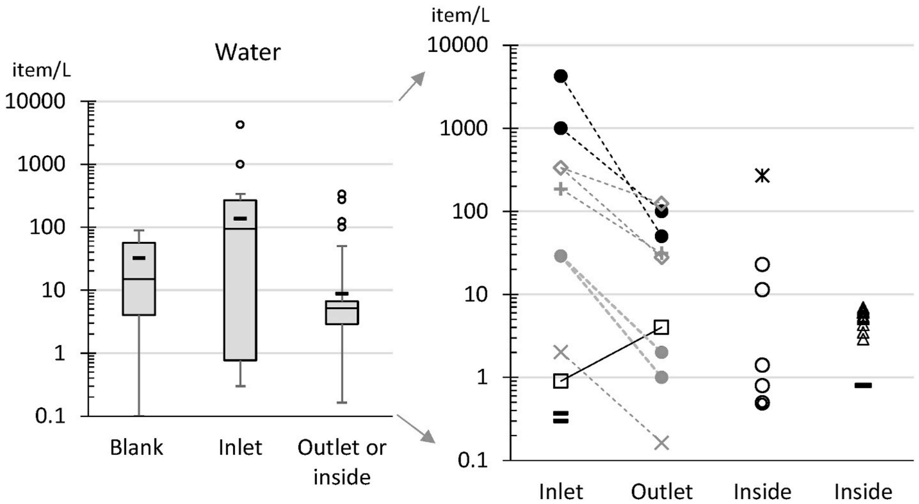

Fig. 1. Left: box-and-whisker plot of all stormwater data gathered in the review; dots above the boxes are outliers. Right: disaggregated data indicating inlet and outlet, when available, or inside the SUDS systems. Ponds are in black colour, bioretention cells or filtration systems are in grey colour. Different symbols are used for each study: ● Coalition Clean Baltic (2017); ▰ Liu et al. (2019b); × Gilbreath et al. (2019); ⁎;Olesen et al. (2019); •Pankkonen, 2020; ▱ Ziajahromi et al. (2020); ━━Boni et al. (2022); ◇ Lange et al. (2021, 2022); + Smyth et al. (2021)[1]; △ Yu et al. (2021). [1]Data consider plastic and non-plastic microparticles.

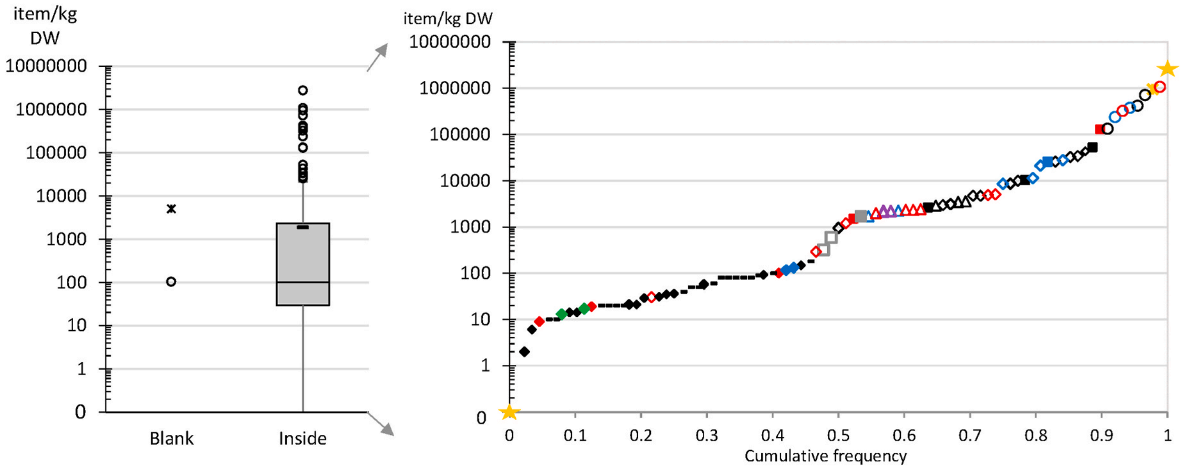

Fig. 2. Left: box-and-whisker plot of all sediments or filter media data gathered in the review; dots above the box are outliers. Right: disaggregated and sorted data; colours indicate different land uses: residential–black, industrial–red, commercial–blue, highway–grey, open space–green, tourism areas–purple, varied or no specified–yellow. Different symbols are used for each study: ▰ Liu et al. (2019b); ⁎; Olesen et al. (2019); ♦ Townsend et al. (2019, for this study the main land use in each wetland has been indicated in colours); ▱ Ziajahromi et al. (2020); △ Yu et al. (2021); ★ Koutnik et al. (2022a; only min and max are shown); - Mbachu et al. (2022); ◊ Lange et al. (2023); ○ Rasmussen et al. (2023). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

230 items/L (median particle concentration in stormwater inlet) to 26.5 items/L (median particle concentration in bioretention cell effluent).

It can be considered that inlet concentrations found in the revised literature (less than 1 to 4250 items/L), are representative for urban stormwater if compared with studies focused on stormwater (Järlskog et al., 2020; Shruti et al., 2021; and Zhu et al., 2021). In comparison to treated wastewater concentrations, which vary from 0 to 447 items/L (Sun et al., 2019), MP abundance inside or at the outlet of SUDS, cannot be neglected. Hence, there is room for improvement in the SUDS design to optimise MP retention and to discharge cleaner effluents into downstream environments. Nonetheless, we should recall that outlet or inside samples are at levels similar to blanks concentrations. Some design suggestions are set out in section 7.

Results from Jakubowicz et al. (2022) are not included in Fig. 1 because they are presented in other units (μg/m^3). They found a significant reduction of MPs from the inlet (0.56–104.77 μg/m^3, depending on the polymer) to the outlet (0–23.61 μg/m^3) of a multistage constructed wetland.

In sediments or filter media, concentrations also show wide variability and data from different studies tend to be grouped. For instance, sediments sampled by Townsend et al. (2019) and Mbachu et al. (2022), were in the lower range of concentrations (2–180 items/kg), Yu et al. (2021) in the middle; and Liu et al. (2019b), Lange et al. (2023), Rasmussen et al. (2023) and Olesen et al. (2019) reported larger concentrations. Koutnik et al. (2022a) found a wide range of variation (0–2.8·10^6 items/kg), reporting the highest value among the reviewed studies. The fact that Rasmussen et al. (2023) have all their results in the upper range is because they sampled road dust deposited on the surface of permeable pavements, while the others are sediments inside urban wetlands or bioretention structures, where the road dust washed-off by the runoff is deposited on the bed of these SUDS. Thus, the samples taken from the latter are a mixture of the dust and dirty entering the SUDS with the original clean sediment.

According to spatial distribution of MPs, several authors have addressed the fate of MPs in the studied SUDS (Ziajahromi et al., 2020; Koutnik et al., 2022a; Mbachu et al., 2022; Lange et al., 2023). In general, these studies found that MP concentration was significantly higher in the top layers of sediments or filter media (0–2 or 0–5 cm), and their concentration exponentially decreased with depth (Koutnik et al., 2022a; Lange et al., 2023). Normally, MP and overall plastic concentration decreased from the inlet from the inlet to the outlet (Ziajahromi et al., 2020; Mbachu et al., 2022) although in other cases the distance from the inlet was not significantly influential (Lange et al., 2023). In spite of these findings, the actual fate of MPs cannot be fully determined because of their potential fragmentation into particles smaller than the detection size, as discussed by Lange et al. (2023).

Results from Klöckner et al. (2019) and Eisentraut et al. (2018) are not included in Fig. 2 as MP or TRWP abundance was expressed in terms of mass (mg/g). The former reported a concentration in a SB of 130 mg/g, which was somewhat higher in the site close to the inlet of a subsequent SRF (150 mg/g). The results significantly decreased along the SRF, reaching 16 mg/g at 35 m to the discharge point. A significant decrease in concentration was also noted at two consecutive SP, from 2.0 to 0.38 mg/g respectively. Important differences in concentration between the two infrastructures are due to different traffic conditions and the surrounding environment. Eisentraut et al. (2018) monitored the same SB as Klöckner et al. (2019) obtaining lower concentrations (less than 1 mg/g and around 9.5 mg/g, depending on the polymer), likely due to the use of different methodology. These concentrations are higher than those reported by Liu et al. (2019b) or Olesen et al. (2019), who estimated the concentration in terms of mass from particles abundance and their density. A possible reason could be that the latter did not identify tire particles and consequently they were not accounted in mass estimation. Rasmussen et al. reported concentration varying between 8.1 and 122.3 mg/kg for MP and between 0 and 2868 mg/kg for tyre wear particles. As counting and spectrometry methods (Raman or FTIR) cannot completely confirm the presence of tyre wear particles, which are abundant in urban runoff, it would be of interest to combine spectrometric and thermal degradation methods.

Several factors can lead to such large differences in the abundance of MPs: methodological aspects, land use, quantity and quality of inflows, meteorological conditions (rainfall intensity and depth, antecedent dry days, etc.), frequency in urban cleansing, catchment area to SUDS area ratio, age of the SUDS or time elapsed since last dredging or replacement of filter media, wetland hydromorphology (area, depth, hydraulic retention time, etc.), sediment resuspension, or the presence of gross pollutant traps or forebays, among others. Considering all these factors, the only one that can be harmonised across studies is the methodology, which highlights the need for an internationally agreed procedure.

Some authors found a relation between MP concentration in water or sediment/filter media and land uses. However, there is no clear trend when all the data are represented together (Fig. 2). Townsend et al. (2019) reported a negative correlation between proportion of open space and MP concentration in sediments, whilst the correlation with the proportion of industrial area and the dwelling density were positive. These both correlations were confirmed by Werbowski et al. (2021), who also showed positive significant correlation between imperviousness and stormwater concentration. Other correlations tested by Townsend et al. (2019), such as size or population density, other land uses, and catchment size were non-significant. Yu et al. (2021) obtained the maximum water concentration in a wetland park located in an industrial area. MP concentration declined through three wetland parks connected by a river, suggesting that wetlands effectively removed MPs from water. These authors analysed sediments as well, finding a higher concentration of MPs respect to water. In sediments, the highest concentration was found in a residential area, maybe because these water bodies were closed without external disturbance, thus facilitating sedimentation process. Conversely, water parks connected to rivers or with ornamental fish had less MPs in sediments, indicating a poorer sedimentation process in these cases (Yu et al., 2021). Liu et al. (2019a, b) found a significant correlation between MP concentration in water samples and land use, whereas this correlation did not exist in sediments.

The influence of further variables on MP concentration in water and sediments was evaluated. MP abundance in sediments was positively correlated with hydraulic loading (Liu et al., 2019b). The influence of maximum rainfall intensity was statistically significant if fibers were excluded from the concentration in urban runoff, and antecedent dry days (ADD) also had a positive correlation with runoff microparticle concentration, though it was not statistically significant (Smyth et al., 2021). Other climatic variables analysed by Smyth et al. (2021), such as mean rain intensity, rain duration, rainfall depth, runoff flow rate and volume, were not significantly correlated with microparticle concentration in urban runoff. In contrast, precipitation depth was found to correlate positively with MP load in urban runoff (Piñon-Colin et al., 2020). Werbowski et al. (2021) supported the positive trend between maximum-2h storm intensity and concentration, and the non-dependence on total storm rainfall, contrariwise the correlation with ADD was too weak.

Finally, the influence of SUDS age and the presence of forebays (FB) or gross pollutants traps (GPT) on MP concentration in sediments or filter media has been addressed by some authors (Mbachu et al., 2022; Lange et al., 2023). Lange et al. (2023) found a moderate negative correlation between MP concentration in surface layer of filter media and age, while no correlation was found by Mbachu et al. (2022). Analysing together data from different studies a general positive trend can be observed but with a weak correlation ($r_{Pearson} = 0.23$, $p > 0.05$) (Fig. S1). Data from Liu et al. (2019b) present a positive correlation although non statistically significant ($r_{Pearson} = 0.67$, $p > 0.05$). Regarding the presence of FB or GPT, Mbachu et al. (2022) found a strong negative correlation, i.e. the MP concentration in sediments from BRS with GPT were in general lower (Fig. S2). The concentrations measured in sediments from the FB were in general higher than in the filter media, although not significantly different (Lange et al., 2023).

In fauna, Olesen et al. (2019) took samples of three-spined sticklebacks (*Gasterosteus aculeatus*) and young newts (*Triturus vulgaris*) and detected a high concentration of MPs ($3.4 \cdot 10^5$ items/kg; 65 items/ind.). The authors highlighted that sediment and fauna samples were concentrated by several orders of magnitude with respect to the water matrix. Su et al. (2019) sampled *Gambusia holbrooki* from nine stormwater wetlands and analysed head and body separately because the fish size was too small to extract gills and guts. They found that the abundance in the body (0.60 ± 1.33 items/ind.) was significantly higher than in head (0.11 ± 0.44 items/ind.) in terms of items/ind., whereas non-significant differences were found in terms of items/g (1.94 ± 3.82 and 3.10 ± 10.13 items/g respectively). This finding led the authors to conclude that the occurrence of MPs in gills was more random, whereas ingestion could be considered a primary pathway of MP uptake. Moreover, they assessed the influence of gender, size, and weight of fish. The abundance of MPs in body was significantly correlated with size and total weight. Female individuals had more and more diverse MPs in their body than male individuals, which contained almost only fibers. The main explanations given by the authors were that female individuals caught were generally more prominent than male counterparts and that they have different feeding behaviour. Females tend to feed in deeper waters, close to sediments, which are believed to be a final sink of MPs because of settling processes (Su et al., 2019; Olesen et al., 2019). In the SWPs studied by Laplaca and van den Hurk (2022), an average of 9 items/ind. and 7.9 suspected tire wear particles per individual were accounted.

5.3. Microplastics properties in SUDS

5.3.1. Shapes

The analysis of microplastic particle morphology was conducted in only 13 of the 23 revised studies. Considering the water matrix, fibers were the most dominant shape (Fig. 3). Generally, when the presence of MPs is analysed in the sediment, fragments are detected in the greatest quantity. This could be explained by the existence of a direct correlation between shapes, materials, size particles, and its ease of being affected by land uses, hydrodynamics, and meteorology, such as wind and rain (Chen et al., 2020). A wider variety of shapes were identified in fauna, which consisted of fibers, fragments, films, pellets and suspected tire wear particles. Only the studies developed by Rasmussen et al. (2023), Jakubowicz et al. (2022), Koutnik et al. (2022a, b), Lange et al. (2022), Pankkonen (2020), Liu et al. (2019b) and Coalition Clean Baltic 2017 (2017) did not analyse shape distribution, meanwhile Lange et al. (2023) and Boni et al. (2022) did not quantify MP morphologies detected in their experiments.

Fibers represent a major fraction of MPs, especially in water inlet and outlet (Fig. 3). This finding can be related with the generally lower settling velocity of fibers (0.39–6.5 cm/s, Waldschlä ger and Schüttrumpf, 2019; 0.1–0.55 mm/s, Nguyen et al., 2022), compared to fragments or spheres (0.5–11.2 cm/s and 1.6–18.4 cm/s respectively, Waldschlä ger and Schüttrumpf, 2019). Furthermore, some factors, such as length, orientation or bending, affect the magnitude of settling velocity for fibers with length between 2 and 6 mm, whereas settling velocity do not significantly depend on their orientation or curliness for short fibers (≤1 mm) (Nguyen et al., 2022). These authors found that curliness of fibers longer than 2 mm can hinder settling up to 1.75 times due to an increase in drag force (Nguyen et al., 2022). It is remarkable that these studies focused on fibers longer than 1 mm, so the behaviour of smaller fibers is a research field to cover.

5.3.2. Polymers

In relation to MP composition, all the revised studies considered polymer identification, except Koutnik et al. (2022a, b) and Laplaca and van den Hurk (2022). Petroleum-based plastics, concretely, polyethylene terephthalate (PET), polyethylene (PE), polystyrene (PS), polypropylene (PP) and polyvinyl chloride (PVC) were present in a major number of the considered studies. The fact that these polymers were the most abundant, might be because these are the most demanded plastics for human's activities and products, such as food packaging, automotive parts, floor and wall covering, bottles, bags or synthetic textile among others, and thus, degraded and deposited in the environment (PlascticsEurope, 2020).

In the water matrix, inlet and inside samples had major presence of PP particles than in outlet samples, in which PE, PET and PP showed similar quantities (Fig. 4). It is noteworthy that PET is present in outlet samples, even though its density is higher than that of water (Prata et al., 2019). This might be because PET could be in form of fibers, which have a settling velocity lower than fragments or spheres, as explained in the previous section.

Looking at the sediment or filter media matrix, particles of PP were found in major quantities than other polymers. This finding contrasts with the fact that PP is less dense than water (Prata et al., 2019), and therefore tends to float rather than sinking. In this case, physical and biological processes like degradation or biofilm formation on PP particles, may increase particle density and therefore, encourage sedimentation. However, in the case study of Mbachu et al. (2022), low density PE was the most common polymer (50%), followed by PP (34%).

Interestingly, Lange et al. (2022, 2023) found that EVA and EDPM rubber were also frequently observed in highway stormwater, sediment and filter media, which may differ from other studies that did not report results on black particles, possibly due to interferences and difficulties in identifying TWRP, as discussed in section 4.4.

According to polymers found in fauna samples, PET was the most frequent. It must be noticed that feeding behaviours of fauna, play an important role in finding different types of MPs. For instance, pelagic fauna would have access to buoyant MPs, mainly PET fibres, while benthic fauna would be exposed to different types of MPs settled in debris (Su et al., 2019).

5.3.3. Size relation

Distribution of particles by size presents a wide variability according to the fractions considered in the investigations. Going through the selected studies, frequent size sections used to differentiate between smaller and bigger particles were 10–500 μm and 500–2000 μm respectively. Regarding the sampling matrix, information provided by authors is diverse and not homogeneous enough between studies.

In the water matrix, Coalition Clean Baltic (2017), Jakubowicz et al. (2022) and Lange et al. (2021, 2022) found that most of the plastic particles were detected in the small size fraction, probably because of a proper sedimentation process of large particles. Lange et al. (2022) also highlight the variability of MP concentration in the small size fraction due to the influence of rain events characteristics. Greatest MP

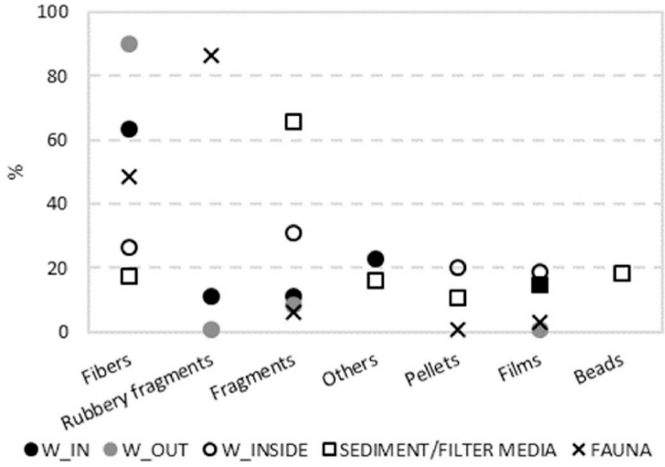

Fig. 3. Abundance of microplastic shapes found in water inlet (W_IN), inside (W_INSIDE) and outlet (W_OUT), sediment/filter media and fauna samples. Data represent the number of shaped particles, in percent average, from the reviewed studies.

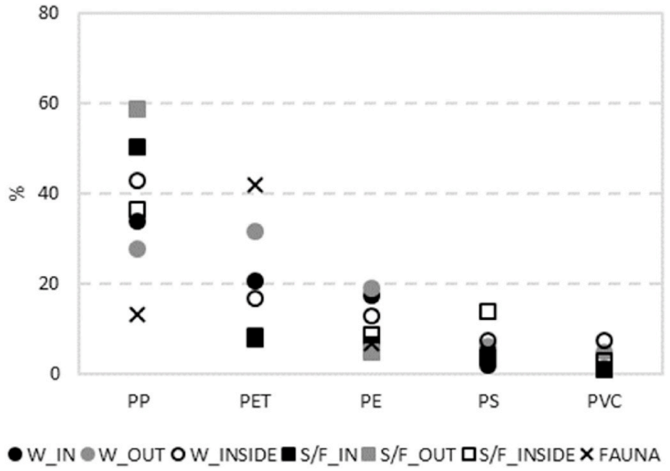

Fig. 4. Abundance of the five most common polymers found in water inlet (W_IN), inside (W_INSIDE) and outlet (W_OUT), sediment or filter media inlet (S/F_IN), sediment or filter media inside (S/F_INSIDE) and sediment or filter media outlet (S/F_OUT), and fauna samples. Data represent the number of polymer particles in percent average, from the reviewed studies.

concentrations were captured when high peak flows produced by severe rain events took place. Other authors relate size particle with shapes and polymers. According to Liu et al. (2019a) findings, larger particles were mostly of PP and shaped as fragments, films, fibers, and pellets, whilst smaller particles were predominantly plump ellipsoids. In contrast, Yu et al. (2021), observed that these small plastics were fragments and fibers. Based on the sampling point, Ziajahromi et al. (2020) found that smaller MPs were detected in outlet water samples, while larger particles in the inlet water samples. However, Smyth et al. (2021) and Werbowski et al. (2021) obtained that the most common particles found at both water inlet and outlet of the BS, correspond to small size. Smaller particles are easier to transport than bigger ones and escape more easily from the retention system.

As it occurs on the water matrix, small plastic particles were predominant in sediment and fauna samples. In case of sediment or filter media, Mbachu et al. (2022) and Liu et al. (2019b) found that small size particles concentration decreased as particle size increased. According to the sampling point, Mbachu et al. detected larger particles in the inlet, than those from the middle and outlet sampling locations. This fact suggests that bigger particles can settle faster, accumulating in the inlet sediment. Additionally, Yu et al. (2021), observed that most of the small particles were fragments and fibers.

In relation to fauna, Laplaca and van den Hurk (2022) and Su et al. (2019) detected that small size particles were prevalent in biota. Looking at Olesen et al. (2019), who sampled the three matrices (water, sediment, and fauna), it was found that particles size in water and its fauna was rather similar, while significantly smaller than in the sediments. This fact can be explained by a fast sedimentation of bigger particles, together with feeding of aquatic fauna of small suspended or buoyant particles.

6. Microplastic retention efficiency of SUDS

According to the analysed literature, it can be strongly believed that SUDS are an effective solution for MP management, in terms of particle reduction from stormwater runoff. Only studies focused on BS, SWP, SF and UPWB provide efficiencies from the experiments, demonstrating very similar high performances in MP reduction.

Gilbreath et al. (2019) estimated a reduction of 91% in average between inlet and outlet of the BS. Further, MP removal efficiencies by particle size were obtained as 100% for MPs >500 μm, 81% for MPs between 355 and 500 μm, and 55% for MPs between 125 and 355 μm.

Over the two-year study period carried out by Smyth et al. (2021), high reductions of microparticle (plastic and non-plastic) load were provided by the BS, ranging from 92% to 100%, considering all sizes together. Sorted by sizes, median microparticle concentrations were reduced by 76% for the 300–500 μm size fraction and >95% for the other three size ranges.

MP tend to accumulate on the surface layers of bioretention filter media (Lange et al., 2023). As part of the stormwater treatment train, the BS studied by Lange et al. (2021, 2022) showed a removal efficiency of 88%. Comparing performances between the vegetated BS and the other SUDS element of the treatment train, the bioretention area worked significantly better than the SF at particle retention, which efficiency obtained was of 47%. Vegetation probably has positive influence in the MP removal efficiency, but additionally, it also offers multiple benefits such as: carbon fixation, enhanced biodiversity, landscape integration, greater and more varied surface area for biofilm formation (important for biodegradation of organic compounds, and hence greater probability for MP biodegradation), and oxygen supply among others. Very high removal efficiency in SF was obtained by Pankkonen (2020), ranging from 95% (for 90–300 μm), 97% (for 300 μm - 1 mm) and 100% (for >1 mm).

Two studies quantified the performance of SWP for MP retention. Olesen et al. (2019) provided a rough first estimation of the retention efficiency. Despite of an assumed uncertainty in the calculations addressed, the results showed an efficiency of 85%, which is rather similar to particular matter performance in SWP. Hence, it is quite evident that this SUDS technique acts as an important sink of MPs from urban areas. Coalition Clean Baltic (2017) concluded that SWP could suppose efficient barriers to tackle MP pollution. Efficiencies obtained in MP retention were >90% for 20–300 μm and >73% for >300 μm size fractions.

In the constructed wetland studied by Jakubowicz et al. (2022), the reduction efficiencies ranged from 77.16 to 100% depending on the polymer type. These results contrast to the low efficiency (28%) of the constructed wetland studied by Pramanik et al. (2020). Despite the lack of data to quantify effectiveness of UPWBs to function as sink of MPs, it can certainly be affirmed that sedimentation processes that occur in this SUDS type, provide fundamental basis for MP retention. The presence of these pollutants in the sediment, demonstrates that UPWBs can protect the receiving environments from MP pollution (Townsend et al., 2019; Yu et al., 2021; Ziajahromi et al., 2020).

7. Future perspectives

Several research fields, addressed so far by one or few studies, have been identified and should be further investigated in the future for better understanding:

- The role of vegetation in MP sequestration.
- The fate of MPs in the vertical and horizontal profiles of sediment or filter material, which can provide information on how incoming pollutant loads have been retained in the system, as well as signs of biodegradation.
- The evaluation of MP concentration in different matrices (water, sediments or filter media, fauna at different levels of the trophic web) to assess potential accumulation and biomagnification processes.
- To expand research on other SUDS techniques such as PPs, vegetated swales or engineered tree pits, among others.

Based on the current state of knowledge, a collection of suggestions to reduce the presence of MPs in the environment are described and encompassed in the following aspects:

7.1. *Implementation of smart urban services*

The intensification of street cleaning tasks in areas that receive high pollution loads, or the placement of flip-top lids on litter bins to avoid waste blowing. It would be of interest to complement these actions with public awareness campaigns and the regulation of single-use products.

7.2. *The study of other SUDS techniques for microplastic retention*

Bioretention areas, ponds, or wetlands are the SUDS solutions more deeply studied for MP retention purposes. These SUDS structures provide effective management of first-flush (Andrés-Doménech et al., 2021). However, these events can lead into resuspension of contaminated sediment that reach the structure, with an increase in pollutant load at outflow point (Ziajahromi et al., 2020). An interesting alternative to complement the previous techniques, are vegetated swales. These naturalised channels may provide runoff storage, conveyance, infiltration, and particle settling, based on retention and interception processes (Andrés-Doménech et al., 2021).

Scientific sources reveal that SUDS contribute to remove total suspended solids (TSS) among other pollutants (O Nnadi et al., 2019). This contaminant can be used as an indicator of possible presence of MPs, due to a significant linear correlation found by between these two pollutants (Buwono et al., 2021; Wang et al., 2020). Filtration-based SUDS trap pollutants within the aggregate or on geotextile layers, and avoid sediment loads discharges to receiving environment. For example, filter drains could effectively retain MPs from stormwater, as they can reduce

TSS by 76% (Andrés-Valeri et al., 2014; Lucke et al., 2014). Further, multiple studies have verified the effectiveness of permeable pavements (PPs) in TSS removal. According to Kamali et al. (2017), PPs performance can vary between 72% and 100%. Hernández-Crespo et al. (2019) and Fernández-Gonzalvo et al. (2021) demonstrated very high efficiencies up to 99% for TSS retention, even under high degree of pollution build up and intense rainfall. Just one research has put interest in the role that PPs could play as possible sink for MP. In this regard, despite the lack of knowledge in how PPs function and how efficient are, Rasmussen et al. (2023) suggest that the porous structure of PPs could retain a significant fraction of MPs generated on roads.

7.3. Design improvement suggestions

Although the studied SUDS techniques have shown high efficiency in terms of MP reduction, there is still further work to investigate the behaviour and enhancement of these nature-based solutions.

With the aim of reducing floating particles in SWPs and UPWBs, it would be of interest to incorporate vegetation in the design of these structures. For example, consideration of floating macrophytes as complement, following the same line as Ziajahromi et al. (2020). The roots of the plants provide entrapping/filtration of suspended particles and creates laminar flow conditions between the root mat and the bottom and encourage sedimentation processes (Oliveira et al., 2021). Another suggestion is to implement vegetated or non-vegetated filtration structures at the end of the treatment system, which may retain higher number of floating particles (Townsend et al., 2019). Ziajahromi et al. (2020) propose to investigate the sustainability of construction materials to avoid MP release to the environment, although they did not found evidence of MP pollution derived from the floating plastic structure. Also, the installation of baffles near the outlet may help to prevent the discharge of buoyant MPs into the receiving environment. Another option to improve efficiency of wetlands or ponds, would be to retrofit them into a treatment train, through the incorporation of an additional SUDS downstream, based on filtration process (bioretention areas, infiltration basins, rain gardens, etc.). In the design phase, the settling velocity of MP fibers should be considered for sizing of sedimentation-based SUDS, provided that space is available.

In relation to improvements on BS, future thoughts might consider the effects of filtering material on clogging, an optimal ponding volume/depth ratio, and even the type of vegetation to incorporate at the bioretention structure, as Smyth et al. (2021) and Lange et al. (2022) suggest. Finally, some authors have observed an insufficient removal of small plastic particles (<100 μm) in GPT and its possible remobilization during rain events (Lange et al., 2022). This may arise in re-thinking the GPT concept, for example, through the incorporation of superficial filtering baffles to trap remobilized particles.

8. Conclusions

Urban runoff is considered an important source of MP pollution. Although several types of SUDS have been evaluated in the literature as part of the measures to tackle this worldwide problem, there is a lack of knowledge in the application of this technology. Sedimentation-based systems, such as wetlands or ponds, and filtration-based systems, such as bioretention cells or gardens, have been shown to effectively retain a significant number of MPs. Indeed, outlet or inside system concentrations are at similar levels to blank concentrations. Nevertheless, it is considered that efficiencies could be enhanced if the retention of MPs was considered as one of the main objectives at the design stage. Some design improvements are proposed in this paper. Future studies should carry out integrated event samplings to estimate event mean concentrations and total MP loads entering and leaving the systems. PP, PE, PET and PS are the most frequent and abundant polymers in urban runoff, due to high consumption in a wide variety of urban products and activities. Fibers and smaller particles are the most challenging fraction, as their retention efficiency is lower. Maximum rainfall intensity, antecedent dry days, rainfall depth, land use, dwelling density, imperviousness, hydraulic loading, SUDS age, and the presence of forebays or gross pollutant traps have been influential variables on the abundance of MPs in some of the studies, although not always statistically significant. The assessment of the fate of MPs by some studies indicates that they are more concentrated in the sediment or filter media near the inlet, as well as in the shallower layers, thus indicating that sedimentation and filtration are important retention mechanisms. This, together with the existence of a correlation between total suspended solids and MP concentration, makes TSS a potential indicator of MP pollution. A wide variability in methods and reporting data format has been found. This makes it difficult to process the data together, and draw conclusions about the performance of SUDS systems, or the influence of certain variables. Therefore, there is a need to develop an internationally agreed methodology for MP sampling and analysis in urban runoff and SUDS.

Declaration of competing interest

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.137197.

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