Abundance, distribution, and composition of microplastics in the filter media of nine aged stormwater bioretention systems

Katharina Lange a,*, Robert Furén a, Helene Österlund a, Ryan Winston b,c,d, R. Andrew Tirpak b, Kerstin Nordqvist a, Joseph Smith b, Jay Dorsey b, Maria Viklander a, Godecke-Tobias Blecken a

HIGHLIGHTS

• Occurrence and accumulation of microplastics in aged bioretention systems.
• Determination of polymer types including black particles.
• Microplastics are accumulated mainly in the filter media top layer.
• Highest microplastic concentrations in the forebays.
• Up to 59% of the microplastics in the filter media are black particles.

ARTICLE INFO

Handling Editor: Hyunook Kim

Keywords: Biofilter, LID, Rain garden, Plastic pollution, Soil media, Urban runoff

ABSTRACT

Bioretention systems are designed for quality treatment of stormwater. Particulate contaminants are commonly treated efficiently and accumulate mainly in the surface layer of the bioretention filter material. However, concerns exist that microplastic particles may not show equal accumulation behavior as other sediment particles. So far only two field and two laboratory studies are available on the fate of microplastics in few relatively newly built bioretention systems. Therefore, this study investigated the abundance and distribution of microplastics in nine 7–12 years old stormwater bioretention systems. It was found that microplastics generally accumulate on the surface of the bioretention systems. Microplastic median particle concentrations decreased significantly from the surface layer (0–5 cm) of the filter material to the 10–15 cm depth layer from 448 to 136 particles/100 g, respectively. The distance to the inlet did not significantly affect the surface accumulation of microplastic particles, suggesting modest spatial variability in microplastics accumulation in older bioretention systems. Further, this study investigated the polymer composition in bioretention systems. It was shown that PP, EVA, PS and EPDM rubber are the most abundant polymer types in bioretention systems. Also, it was found that large percentages of microplastic particles are black particles (median percentage of black particles: 39%) which were...
found in 28 of the 33 investigated samples. This underlines the importance of including black particles in microplastic studies on stormwater, which has been overlooked in most previous studies.

1. Introduction

Microplastic pollution is of increasing environmental concern, since particles are widespread in the environment and negative (up to toxic) effects on biota have been reported (Horton et al., 2017). Stormwater runoff is considered to be a major vector for microplastic transport, which is often discharged via separate sewer systems into receiving waterbodies (e.g., Unice et al., 2019; Werbowski et al., 2021; Osterlund et al., 2023). Little is known about how common stormwater treatment technologies are able to sequester microplastics (Stang et al., 2022, 2023). Since a general definition of microplastics is lacking, this study follows the definition in Hartmann et al. (2019) wherein tire and road wear particles are also considered to be microplastics.

In the last 30 years, stormwater management concepts such as water sensitive urban design (WSUD), sustainable urban drainage systems (SUDS), and low impact development (LID) have been implemented in various parts of the world, with the goal to protect downstream aquatic ecosystems from erosion and pollution (Fletcher et al., 2015). Bioretention systems, composed of an engineered filter media (Tirpak et al., 2021) and vegetation, have been implemented in this context for flow attenuation and pollution control (Hunt et al., 2012; Winston et al., 2016; Flanagan et al., 2018). Often bioretention facilities are equipped with a pre-sedimentation forebay to reduce sediment loads before runoff reaches the filter bed, primarily to reduce clogging.

Previous studies have shown that bioretention systems can effectively remove various particulate contaminants from stormwater, such as total suspended solids (TSS), heavy metals, and particulate phosphorus (e.g., Davis, 2007; Flanagan et al., 2018; Hatt et al., 2009). Some recent studies have shown that microplastics are also removed by bioretention systems, as summarized by Stang et al. (2022) and Osterlund et al. (2023). Gilbreath et al. (2019) found that concentrations of microplastic particles (>125 μm) were reduced by 83–95% by a rain garden treating road runoff in California, USA. Smyth et al. (2021) reported that >106 μm microplastic particles were reduced in runoff from a parking lot by a bioretention cell in Ontario, Canada, while Lange et al. (2021) and Lange et al. (2022a) showed that a bioretention cell in Sundsvall, Sweden, reduced the concentrations of microplastic, rubber and bitumen particles in 20–300 μm size fractions in highway runoff. Filtration is regarded as the main process responsible for the removal of microplastic particles in bioretention systems (Smyth et al., 2021).

However, these studies do not reveal where in the filter the microplastics are trapped which has, inter alia, impact on their long-term performance including the need for (partial) replacement of the filter material as discussed by Al-Ameri et al. (2018) for metals and Furén et al. (2022) for organic micropollutants (for the same filters as included in this study). Further, knowledge on accumulation and pathways of microplastic in the filter material will also contribute to and understanding the treatment processes of microplastics which might vary from other sediment e.g. due to different polymer types, their shape and density (Osterlund et al., 2023).

Particulate pollutants tend to accumulate in the surface layer of bioretention systems (Al-Ameri et al., 2018). However, results of laboratory scale column experiments indicate that microplastic particles could also be transported into deeper filter media layers as a result of wet-dry cycles, freeze-thaw cycles or macropores created by plant roots (Koutnik et al., 2022a; Kuoppamäki et al., 2021; O’Connor et al., 2019). Polyester type has been shown to affect the mobility of microplastic particles in sand soil columns by O’Connor et al. (2019), who found that polyethylene (PE) particles have a higher mobility than polypropylene (PP) particles, given their lower density compared to PE particles. Lange et al. (2020) suspected that polymers with lower density might be exported from the filter when high flow events are bypassed through an overflow pit structure.

To date, there is limited knowledge of the occurrence and distribution of microplastic particles in bioretention filter media. Only two published studies have reported their abundance and distributions in soil and/or filter media in the field (Koutnik et al., 2022b; Mbachu et al., 2022), while two others have addressed their fate in filter media in laboratory experiments (Koutnik et al., 2022a; Kuoppamäki et al., 2021). Koutnik et al. (2022b) measured microplastic concentrations in soil samples of 14 stormwater control measures (SCMs, mainly swales and bioretention) at various locations in Los Angeles, USA. They found that microplastic concentrations decreased significantly from the SCM surface (mean concentration 472 particles/g soil) to a depth of 8–10 cm (mean concentration 149 particles/g soil). A detailed investigation of one bioswale indicated that the decrease was exponential and that most of the microplastics were removed in the upper 5 cm of the soil. Similar results (i.e., the removal of most microplastics in the upper centimeters of filter media) were obtained in lab-scale column studies by Koutnik et al. (2022a) and Kuoppamäki et al. (2021), who focused on the fate of irregularly shaped polypropylene particles and polyethylene beads (<10 μm) in soil columns. Mbachu et al. (2022) found that the horizontal distribution and composition of microplastic particles in a bioretention system in South East Queensland, Australia. They reported that the microplastic concentrations in the bioretention systems did not depend on distance from the inlet (i.e., little spatial variability in microplastic accumulation was observed), and the most abundant particles were composed of low-density polyethylene and polypropylene (accounting for 50% and 34% of total counts, respectively). In addition to filtration processes, findings summarized by Shamskhany et al. (2021) regarding relevant phenomena in marine environments suggest that sedimentation processes could also have an impact on the accumulation of microplastics (especially non-buoyant particles) in bioretention systems. Sedimentation of microplastics probably differs from most other particles conveyed by stormwater (Al-Ameri et al., 2018) due to differences in physicochemical characteristics that affect buoyancy (Shamskhany et al., 2021). Accordingly, Mbachu et al. (2022) found that microplastic concentrations had no significant spatial variability in bioretention systems. However, they only investigated composite samples covering the whole filter depth, thus deposition patterns near the surface of the filter media may have been overlooked.

Few studies have been performed to-date which characterize the vertical and horizontal distribution of microplastics in bioretention systems (Koutnik et al., 2022b; Mbachu et al., 2022). An important limitation of Koutnik et al. (2022b) is a general inability to analyze concentrations and distributions of black particles due to the analytical methods used (Wagner et al., 2018). This excludes important traffic-related microplastic particles such as (black) rubber and bitumen particles that are abundant in urban stormwater (e.g., tire and road wear particles, Järlskog et al. (2020); Järlskog et al. (2021); Lange et al., 2021; Lange et al., 2022a). In addition, attention has focused almost exclusively on recently constructed stormwater controls (Koutnik et al., 2022b; Mbachu et al., 2022). Despite their impact on the maintenance of bioretention (especially replacement of filter material; Furén et al., 2022), empirical knowledge of microplastic accumulation patterns in older bioretention facilities is nonexistent.

Bioretention facilities are often equipped with a small pre-sedimentation forebay for energy dissipation and removal of sediment (Bleczen et al., 2017; Johnson and Hunt, 2016). However, little research has been done to assess the actual effect of these (usually very small) forebays on water quality. Johnson and Hunt (2016) and
Purvis et al. (2019) have shown that forebays can accumulate sediments (and particle bound pollutants). However, no studies have evaluated the effect of small forebays on microplastics removal and/or if microplastics are present in the sediment captured in these design features. Given their potential to remove sediment as observed by Johnson and Hunt (2016) and Purvis et al. (2019), microplastics may also be trapped by forebays. However, Lange et al. (2021, 2022a, 2022b), who addressed effects of a larger pre-sedimentation gross pollutant trap as part of a bioretention treatment train, found that it did not significantly influence microplastics, sediment, and metal removal. These partly conflicting results motivate further assessment of forebays.

To improve the scientific understanding of the fate of microplastic particles in bioretention systems, we have investigated vertical and horizontal distributions of microplastic particles in the filter media of nine aged bioretention systems. Additionally, microplastics were quantified in samples of forebay sediments collected from six of these systems. Detailed characterization of the abundance and distribution of specific polymer types in the samples provided indications of the potential sources of microplastic particles detected and the fates of specific types of microplastics in the filter media. To enable analyses of diverse microplastic particles including black particles, a combined approach was applied including both μ-Fourier transform infrared (μFTIR) and FTIR attenuated total reflectance (ATR-FTIR) spectroscopy. Based on the previous studies summarized above, it is hypothesized that microplastics will accumulate in bioretention, but to varying degrees depending on 1) different polymers, 2) the depth of the filter media, and 3) the distance from the inlet. We hypothesize that a high percentage of the detected microplastic particles are black particles. The forebay may be less efficient in removing microplastics.

2. Methods

2.1. Site description

Sediment sampling was performed at nine bioretention systems in Ohio and Michigan, USA (Supplementary Fig. S1). At the time of sampling, the bioretention systems had been operational for 7–12 years (Table 1). The systems were located adjacent to roads or parking lots in urban areas classified as industrial, commercial, downtown ultra-urban, or mixed residential and commercial (Table 1). Six of the nine bioretention systems had forebays at the inlets (Table 1, Supplementary Figs. S3, S6, S7, S9-S11).

2.2. Sampling

Three filter media samples were collected from each of the nine bioretention systems. In each case, two of these samples were collected from the surface of the filter media (the upper 0–5 cm layer), approximately 1 and 3 m from the inlet (hereafter locations 1 and 2, respectively, Supplementary Fig. S2). At location 1, another sample was taken from 10 to 15 cm depth. At six of the nine bioretention systems, a sediment sample was taken from the forebay by removing sediment attached to the rock and/or accumulated in it. In total, 33 samples were collected and used for this analysis. All samples were taken using a steel spade and collected in 18 × 35 cm transparent plastic (polyamide, PA) bags, which were tightly closed with cable ties. PA was only detected in one of the 33 samples, confirming that significant contamination from the bags did not occur.

2.3. Microplastic analysis

Microplastic contents and polymer types in the 33 samples were analyzed by a commercial laboratory (ALS Scandinavia) after removing natural organic matter and sediment particles by the Fenton reaction and density separation with zinc chloride solution (1.76 g/cm³), respectively. Samples containing substantial amounts of plant material according to visual inspection were subjected to an extra cellulose dissolution step according to Olsen et al. (2020). The samples were analyzed with μFTIR and ATR-FTIR and the size range of analyzed microplastic particles was 40–5000 μm. The concentrations determined refer to dry samples, i.e. are in mg/kg dry weight. To identify the microplastic polymers detected by the μFTIR spectroscopy, the Systematic Identification of MicroPlastics in the Environment (SiMPle) library compiled by Aalborg University, Denmark, and Alfred Wegener Institute, Germany (Primpke et al., 2020) was applied. At the time of analysis the library included reference spectra for 150 types of plastics, including polyethylene (PE), polypropylene (PP), polyurethane (PUR), polyethylene terephthalate (PET), PA, polystyrene (PS), polyvinyl chloride (PVC), ethylene propylene diene monomer rubber (EPDM rubber), polymethyl methacrylate (PMMA), and polyactic acid (PLA). Another library (Spektrum IR, version 10, 6, 2,1159, PerkinElmer, Inc.), which includes 4000 organic and plastic as well as styrene-butadiene rubber (SBR) reference spectra was used to identify plastics detected by the ATR-FTIR spectroscopy.

For quality assurance and control, laboratory blanks were handled and analyzed together with the samples. A limitation of this study is that no field blanks were taken. However, no microplastic particles were found in two of the analyzed samples, indicating that contamination with >40 μm particles was low.

2.4. Data analyses

No detailed statistical analyses of distributions of single polymer types were conducted because, with the exception of PP, 27–97% of the data for all of the polymers were below detection limits (Table 2) prohibiting reliable analyses even with data censoring. Therefore, the sum of all polymer type concentrations at each location at each sampling site was calculated. At two locations, the sum of microplastic particles was below detection limits. These values were replaced by half the detection limits, following Antweiler and Taylor (2008). Detection limits (Table 2) were calculated based on the sample mass used for the microplastic analyses and the filter area size examined with μFTIR/ATR-FTIR. When calculating the percentage of different polymer types in the total number of microplastic particles, only microplastic concentrations above the

Table 1

<table>
<thead>
<tr>
<th>Sampling site</th>
<th>Forebay</th>
<th>Age [yr]</th>
<th>Catchment land use</th>
<th>Catchment Area [m²]</th>
<th>Filter Area [m²]</th>
<th>Loading ratio [ %]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yes</td>
<td>12</td>
<td>Industrial</td>
<td>4500</td>
<td>300</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>10</td>
<td>Industrial</td>
<td>6000</td>
<td>300</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>8</td>
<td>Commercial</td>
<td>750</td>
<td>40</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>7</td>
<td>Commercial</td>
<td>4000</td>
<td>170</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>Yes</td>
<td>9</td>
<td>Downtown Ultra Urban</td>
<td>300</td>
<td>40</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>No</td>
<td>12</td>
<td>Downtown Ultra Urban</td>
<td>6000</td>
<td>50</td>
<td>8</td>
</tr>
<tr>
<td>7</td>
<td>Yes</td>
<td>8</td>
<td>Downtown Ultra Urban</td>
<td>50</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>8</td>
<td>Yes</td>
<td>11</td>
<td>Downtown Ultra Urban</td>
<td>500</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>Yes</td>
<td>9</td>
<td>Residential/Commercial</td>
<td>318 500</td>
<td>950</td>
<td>0.3</td>
</tr>
</tbody>
</table>

* Ratio of the total catchment area to the bioretention filter area.
<table>
<thead>
<tr>
<th>Location in filter</th>
<th>Chemosphere 320 (2023) 138103</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forebay</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>545 15 &lt;15 &lt;15 &lt;15 &lt;15</td>
</tr>
<tr>
<td>4</td>
<td>1020 85 157 &lt;14 &lt;14 &lt;14</td>
</tr>
<tr>
<td>5</td>
<td>15 316 395 &lt;79 &lt;79 &lt;79</td>
</tr>
<tr>
<td>200</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1750 622 49 &lt;16 &lt;16 &lt;16</td>
</tr>
<tr>
<td>8</td>
<td>876 16 &lt;16 &lt;16 &lt;16</td>
</tr>
<tr>
<td>9</td>
<td>101 &lt;1 8 8 8 8</td>
</tr>
<tr>
<td>Location 1 (0.5 cm)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>40 &lt;19 40 &lt;19 &lt;19 &lt;19</td>
</tr>
<tr>
<td>2</td>
<td>172 &lt;14 &lt;14 &lt;14 &lt;14 &lt;14</td>
</tr>
<tr>
<td>3</td>
<td>211 95 24 &lt;24 &lt;24 &lt;24</td>
</tr>
<tr>
<td>4</td>
<td>481 51 732 &lt;25 &lt;25 379</td>
</tr>
<tr>
<td>5</td>
<td>2650 36 90 &lt;19 &lt;19 19</td>
</tr>
<tr>
<td>6</td>
<td>204 &lt;20 &lt;20 &lt;20 &lt;20</td>
</tr>
<tr>
<td>7</td>
<td>1630 612 126 &lt;22 &lt;22 &lt;22</td>
</tr>
<tr>
<td>8</td>
<td>157 &lt;22 &lt;22 &lt;22 &lt;22</td>
</tr>
<tr>
<td>9</td>
<td>34 8 8 8 8 8</td>
</tr>
<tr>
<td>Location 1</td>
<td></td>
</tr>
<tr>
<td>(10.15 cm)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>14 &lt;14 &lt;14 &lt;14 &lt;14 &lt;14</td>
</tr>
<tr>
<td>2</td>
<td>&lt;9 &lt;9 &lt;9 &lt;9 &lt;9 &lt;9</td>
</tr>
<tr>
<td>3</td>
<td>114 50 16 &lt;16 &lt;16 &lt;16</td>
</tr>
<tr>
<td>4</td>
<td>77 &lt;16 &lt;16 &lt;16 &lt;16 &lt;16</td>
</tr>
<tr>
<td>5</td>
<td>1990 184 17 &lt;17 &lt;17 &lt;17</td>
</tr>
<tr>
<td>6</td>
<td>53 &lt;17 &lt;17 &lt;17 &lt;17 &lt;17</td>
</tr>
<tr>
<td>7</td>
<td>443 &lt;27 &lt;27 &lt;27 &lt;27</td>
</tr>
<tr>
<td>8</td>
<td>85 &lt;17 &lt;17 &lt;17 &lt;17 &lt;17</td>
</tr>
<tr>
<td>9</td>
<td>68 &lt;9 &lt;26 &lt;9 &lt;9 &lt;9</td>
</tr>
<tr>
<td>Location 2 (0.5 cm)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>&lt;15 &lt;15 &lt;15 &lt;15 &lt;15 &lt;15</td>
</tr>
<tr>
<td>2</td>
<td>302 &lt;9 18 9 9 9</td>
</tr>
<tr>
<td>3</td>
<td>738 91 91 &lt;30 &lt;30 &lt;30</td>
</tr>
<tr>
<td>4</td>
<td>570 113 23 23 23 23</td>
</tr>
<tr>
<td>5</td>
<td>139 40 &lt;20 &lt;20 &lt;20</td>
</tr>
<tr>
<td>6</td>
<td>414 114 47 &lt;23 &lt;23 &lt;23</td>
</tr>
<tr>
<td>7</td>
<td>1668 359 391 &lt;32 &lt;32 &lt;32</td>
</tr>
<tr>
<td>8</td>
<td>1561 &lt;22 &lt;22 &lt;22 &lt;22</td>
</tr>
<tr>
<td>9</td>
<td>567 39 39 39 &lt;19 &lt;19</td>
</tr>
</tbody>
</table>

Table 2
Microplastic particle concentrations (particles/100 g) in samples from various locations in the bioretention sites. Bold fonts indicate the values above the detection limit. The “<” indicates that the values are below the detection limit.
detection limits were included.

To assess the significance of differences in microplastic concentrations (sum of all polymer types) between the forebay, location 1 (0–5 cm layer), location 1 (10–15 cm layer), and location 2, the Wilcoxon signed rank test was applied following Koutnik et al. (2022b). At location 1, where microplastic concentrations were determined at two depths in the filter media, retardation coefficients (K) were calculated using equations presented by Koutnik et al. (2022b) based on the assumption that the microplastic concentration in bioretention filter media declines exponentially as:

\[ C(z) = C_0 e^{-Kz} \]  

where \( z \) is the depth (cm), \( C \) is the plastic concentration (particles/100 g), \( C_0 \) is the concentration at the surface (particles/100 g), and \( K \) is the retardation coefficient. Correlations between retardation coefficients and median particle size (\( D_{50} \), Supplementary Table 1) were also examined, but using Spearman’s \( \rho \) rather than the scatterplots and regression analyses used in Koutnik et al. (2022b). The particle size distribution was determined by laser diffraction particle size analysis using a LS 13 320 Laser Diffraction Particle Size Analyzer (Beckman Coulter, Inc.). Minitab© 17.2.1 was used for all statistical analyses.

3. Results and discussion

Generally, PP, EVA, PS and EPDM rubber were the most abundant polymer types found in the bioretention filter media (Table 2). Depending on the sample, up to 59% of the microplastic particles were black particles. Distance from the inlet did not significantly affect the concentrations of microplastic particles; however, microplastics were present at significantly higher concentrations in the surface layer (0–5 cm) of the filter media than at 10–15 cm depth.

3.1. Microplastic composition

In total, 17 polymer types were observed in the filter media of the bioretention systems. The greatest diversity of microplastic particles was observed at location 1 in the surface layer (0–5 cm), where all 17 polymer types were identified. At each of the other filter media sampling locations and forebay, between 11 and 14 polymer types were observed (Table 2; Fig. 1).

Both non-black and black particles were observed in 28 of the 33 total samples. The percentage of black particles in these samples ranged from 6 to 59%, with a median of 39%. Overall, 17 types of polymers were found, and thus, in terms of polymer types, the black particles were more variable than non-black particles (nine polymer types). This highlights the importance of selecting laboratory methods that enable analysis of black microplastic particles.

Fig. 1. Microplastic composition at indicated locations of the bioretention systems at sampling sites 1–9. A: Percentages based on concentrations of total particles detected in the samples. B: Particle concentrations/100 g based on total number of particles detected.
PP particles were the most abundant in black and non-black particle pools. They were found in 31 of the 33 samples, across all studied bioretention systems (Fig. 1; Table 2), and were the most abundant type of microplastic detected in 22 of the 33 samples (Fig. 1).

Other frequently observed polymer types were EVA, PS, and EPDM rubber, which were found in 24, 20 and 19 samples, respectively. While the fraction of EVA and EPDM rubber in the microplastic particles occasionally reached percentages up to 60 and 83%, the fraction of PS particles was generally lower with percentages up to 23%. EVA particles were found in samples from six and seven sampling sites at location 1 (both 0–5 cm and 10–15 cm depths) and location 2, respectively, and in forebay samples from four of six sampling sites. PS particles were found mainly in the forebays and surface layers of the filter media (0–5 cm layer of locations 1 and 2), where they were observed at five of six and six of nine sampling sites, respectively. At the 10–15 cm sampling depth at location 1, PS particles were only observed in three of nine samples. EPDM rubber was found at four of six sampled forebays, at five (location 1) and six (location 2) of nine sampling sites in the filter media surface layers, and at four of nine sampling sites at the 10–15 cm depth at location 1.

Microplastic samples generally had few PVC and PE particles, at most 15% and 21% of total particles, respectively. These plastics were found in 15 and 10 of 33 samples, respectively. PVC particles occurred mainly in the forebay (where they were found at four of six sampling sites) and surface layer of the filter media (where they were found at six of nine sampling sites at location 1 and four of nine sampling sites at location 2). PVC particles were only found in the 10–15 cm depth layer at location 1 at one (of nine) sampling sites. PE particles were observed at two of (six) forebay sampling sites, at location 1 (0–5 cm and 10–15 cm depths) at two (of nine) sampling sites, and location 2 at four (of nine) sampling sites.

Occasionally, other polymer types were found in the forebays and/or bioretention filter media: SBR in nine samples, PUR in eight samples, cellulose acetate in four samples, PET and chlorinated PE in three samples, PMMA in two samples and PLA, PA, polyester, phenoxy resin, acrylic color and PCT in one sample.

4. Discussion

Bioretention systems mainly receive microplastic inputs from stormwater, although atmospheric deposition and initial contamination of filter media may also contribute microplastics to these facilities (Koutnik et al., 2022b). The plastic materials identified herein indicate which sources contribute to microplastic contamination in urban catchments. PP, EVA, PS, and EPDM rubber were the dominant polymer types found in the filter media of the bioretention systems. These polymer types are commonly applied plastics and can be found in the surface layers, and at four of nine sampling sites at the 10–15 cm depth at location 1.

Microplastic samples generally had few PVC and PE particles, at most 15% and 21% of total particles, respectively. These plastics were found in 15 and 10 of 33 samples, respectively. PVC particles occurred mainly in the forebay (where they were found at four of six sampling sites) and surface layer of the filter media (where they were found at six of nine sampling sites at location 1 and four of nine sampling sites at location 2). PVC particles were only found in the 10–15 cm depth layer at location 1 at one (of nine) sampling sites. PE particles were observed at two of (six) forebay sampling sites, at location 1 (0–5 cm and 10–15 cm depths) at two (of nine) sampling sites, and location 2 at four (of nine) sampling sites.

Occasionally, other polymer types were found in the forebays and/or bioretention filter media: SBR in nine samples, PUR in eight samples, cellulose acetate in four samples, PET and chlorinated PE in three samples, PMMA in two samples and PLA, PA, polyester, phenoxy resin, acrylic color and PCT in one sample.

4.1. Microplastic concentrations and distributions

4.1.1. Horizontal distribution in the bioretention filter media and forebay

Overall, the microplastic concentrations (sum of all polymer types found) in the top 5 cm layer of the bioretention filter media were similar at both sampling locations 1 and 2 (Fig. 2), indicating that microplastics are distributed across the entire surface of the systems covered by sampling and do not settle completely in the forebay or immediately downstream of the inlet. The microplastic concentrations in the surface

![Fig. 2. Horizontal and vertical distributions of microplastic particles in the nine bioretention systems (concentrations in particles/100 g forebay sediment or filter media).](image-url)
layer close to the inlet varied among the nine sampling sites from 120 to 4270 particles (median: 488) per 100 g of dry soil media. At location 2, microplastic concentrations in the surface layer varied between <29 and 3270 particles (median: 1000) per 100 g. There were no significant differences in microplastic concentrations between locations 1 and 2 according to the Wilcoxon signed rank test (W statistic 24, p = 0.906, estimated median 67).

The microplastic concentrations in the six studied forebays varied between 560 and 17 300 particles (median: 1940) per 100 g. Most estimated microplastic concentrations in the forebays (except one outlier from facility 5; 17 300 particles per 100 g), were in the same range as in the filter media (Supplementary Fig. S12). The Wilcoxon signed rank test revealed no significant differences in concentrations between the forebay and location 1 at 0–5 cm depth (W statistic 4, p = 0.208, estimated median –586), nor between forebay and location 2 at 0–5 cm depth (W statistic 8, p = 0.675, estimated median –310.1).

4.1.2. Distribution of microplastics with depth

Microplastic concentrations were lower at 10–15 cm depth than the surface layer (0–5 cm) in eight of the nine bioretention facilities (Fig. 2, Table 2). This indicates that bioretention systems generally retain microplastic particles in the top layer of the soil media, as is the case with many other particulates (e.g., Hunt et al., 2012; LeFevre et al., 2015). While microplastic concentrations in the surface layer at location 1 varied between 120 and 4270 particles per 100 g, they ranged between <9 and 2380 particles per 100 g at 10–15 cm depth at the same location. Median concentrations fell from 488 particles per 100 g at the surface layer to 155 per 100 g at 10–15 cm depth. Despite the high variations, differences in microplastic concentrations were significant at 0–5 cm versus 10–15 cm (Wilcoxon signed rank test; W statistic 4, p = 0.033, estimated median –1031).

Retardation coefficients were calculated using the equation presented by Koutnik et al. (2022b) based on their assumption that microplastic concentrations in bioretention filter media decrease exponentially with depth. The retardation coefficient is a metric that facilitates comparison of processes at various sites with different plastic concentrations at the surface and at given depths. The microplastic particle concentration decreased at every site between 0–5 and 10–15 cm depths, resulting in positive retardation coefficients between 0.04 and 0.38 K/cm, except at sampling site 1 (Fig. 3).

No significant correlation was found between the retardation coefficients and median particle size. Spearman’s ρ values of –0.200 (p = 0.606) and 0.100 (p = 0.798) were obtained for correlations between the retardation coefficient vs. D50 in the top (0–2 cm) and deeper (5–10 cm) layer, respectively. This indicates that the filter media’s particle size does not significantly influence vertical distributions of >40 μm microplastic particles in bioretention systems, which is supported by similar findings in Koutnik et al. (2022b) for particles >10 μm.

4.1.3. Factors affecting the microplastic concentrations in bioretention filter media

Few correlations were found between microplastic concentration and age of the bioretention system or loading ratio (Supplementary Table S2). For location 1 (top layer) a moderate negative correlation between microplastic concentration and age was found (Spearman ρ = -0.675, p = 0.046). However, the age range of the nine bioretention systems included in this study is small (7–12 years). Including considerably older and/or newly built facilities might have resulted in a clear relationship between microplastic concentration and age. Further, systems with the same age varied in terms if catchment type, ratio of filter area vs. catchment area etc.

5. Discussion

Mbachu et al. (2022) reported total microplastic counts from 0 to 18 particles/100 g. Koutnik et al. (2022b) recorded mean concentrations of 47 200 particles/100 g, with maximum values up to 278 400 particles/100 g in the surface layer (0–2 cm) of filter media of the SCMs they studied. At 8–10 cm depth they recorded mean microplastic concentrations of 14 900 particles/100 g of filter media. The particle concentrations determined in bioretention filter media and forebays in this study (Table 2) were between those recorded in the studies by Mbachu et al. (2022) and Koutnik et al. (2022b).

However, limited comparisons can be made between the results herein and those of previous studies. Reasons for this limited comparability include differences in laboratory methodologies and resulting data, e.g., differences in ranges of microplastic sizes, solutions used for density separations, and differences in microplastic/plastic availability from catchments (Liu et al., 2019b). This also applies to the comparability of studies of microplastic concentrations in bioretention filter media. Although Mbachu et al. (2022) used similar methodologies for plastic identification to those herein (density separation with ZnCl2, and ATR-FTIR), they investigated microplastic concentrations in homogenized samples representing whole biofilter soil depths. Thus, potentially higher surface concentrations may have been diluted by mixture with filter media of deeper soil layers. Koutnik et al. (2022b) investigated microplastic concentrations in 14 SCMs at two depths similar to the sampling points in this study (0–2 and 8–10 cm). However, they used a microplastic analysis method including staining with Nile Red that cannot detect some relevant particles, e.g., particles from tire wear, according to Koutnik et al. (2022b). Nevertheless, much higher microplastic particle concentrations were observed compared to this study, possibly because their smallest detectable particle size (10 μm) was lower than that used in this work (40 μm). Earlier studies have found similar trends, wherein microplastics concentrations increase with decreasing particle size in the stormwater itself (e.g., Smyth et al., 2021; Lange et al., 2021; Lange et al., 2022b; with lowest particle sizes of 106, 100, and 20 μm, respectively). However, at this stage this assumption is not well supported and further bioretention filter media studies including analyses of smaller microplastic particles are needed.

Koutnik et al. (2022b) compared microplastic concentrations in SCM filter media and outside the same SCMs and found no significant differences in particle concentrations between these sampling points. They concluded that besides stormwater inflow, atmospheric deposition is an important contribution pathway for microplastics found in bioretention filter media. Unfortunately, no surrounding soil samples were collected in this study, and so this hypothesis could not be assessed. Further field studies should include such samples to distinguish between microplastics from stormwater and atmospheric deposition as discussed by Osterlund et al. (2023). This could at least partially explain the uniformity in microplastics found in surface layer samples observed in this study. The lack of a general reduction in microplastic particle concentrations...
concentrations with increasing distance from stormwater inlets could also be explained by resuspension and relocation of accumulated microplastics during rain events that raise water levels in bioretention systems. Koutnik et al. (2022b) also hypothesized that microplastic particles may be redistributed, especially those with lower densities, buoyancy-favoring forms, and small sizes (Shamskhany et al., 2021). Similarly, previous studies have shown that microplastic particles are not always influenced by sedimentation processes in stormwater treatment systems (Liu et al., 2019a; Ziajahromi et al., 2020; Lange et al., 2022a). For example, Lange et al. (2022a) found that high concentrations of microplastic particles may avoid retention by passing through an overflow pit attached to a gross-pollutant trap at the inlet of a bioretention system.

The reduction in microplastic concentration from the surface layer (0–5 cm) to the 10–15 cm layer detected in this study indicates that microplastic particles accumulate in the surface layer of bioretention systems, similar to other particulate contaminants (Al-Ameri et al., 2018). Koutnik et al. (2022b) also found that microplastic particle concentrations were higher in the surface layer than in deeper filter media layers in the only other published investigation of the distribution of microplastics with depth in bioretention filter media. They attributed accumulation of microplastic particles in the surface layer to filtration of plastic particles by the filter media. This was also previously suggested by Smyth et al. (2021), who observed efficient treatment of stormwater microplastics by bioretention systems. Similar observations of bioretention systems have been reported by Gilbreath et al. (2019), Lange et al. (2021), and Lange and Al-Ameri et al. (2022b).

Retention coefficients (Fig. 3) were in the same range to those calculated by Koutnik et al. (2022b), although the cited authors recorded higher overall microplastic concentrations and included smaller microplastic particles. We also concur with Koutnik et al. (2022b) that retardation coefficients in the bioretention systems were not significantly correlated with $D_{50}$ values of the filter media. Koutnik et al. (2022b) hypothesized that this could be due to variations among systems in initial microplastic contamination of the filter media, infiltration/flow rates, bioturbation and/or formation of preferential flow paths. In addition, Kuoppamäki et al. (2021) showed that <10 μm microplastic particles (much smaller than those analyzed in other studies) were transported along plant roots and Koutnik et al. (2022a) found that freeze-thaw affects the mobility of microplastics in bioretention filter media. However, these factors were not evaluated in this study and warrant attention in further field experiments. Overall, results presented here and by Koutnik et al. (2022b) indicate that the filter media’s grain size does not significantly influence vertical distributions of >10 μm microplastic particles in bioretention systems. This is promising for the implementation of bioretention systems in regions with cold climates, where coarser filter media is commonly used (Kratky et al., 2017).

Although not significantly different, the microplastic concentrations in the forebays were generally higher than in the filter media, especially at sampling site 5 (Table 2, Supplementary Fig. 512). The sediment in the forebay is mainly stormwater sediment rather than bioretention filter media, as at locations 1 and 2, which may explain the difference. However, the forebay usually has a much smaller surface area than the rest of the bioretention system, which therefore likely removes more plastic particles, despite having lower concentrations. To test this hypothesis more information on parameters such as emptying frequencies of forebay, sediment deposition rates, hydraulic retention time, and microplastic buoyancy would be required. Moreover, six systems with a forebay and three systems without one (as in this study) are too few for rigorous assessment of forebay’s effects on microplastic concentrations in the filter media.

This study shows that microplastics are present in stormwater bioretention facilities. This is a logical consequence of the relatively efficient removal of microplastics in bioretention (Smyth et al., 2021; Lange et al., 2021, 2022a; Oterlund et al., 2023). The presence of microplastics in SCMs has also been described by Koutnik et al. (2022b). So far, to the best of our knowledge, no research has been performed concerning the impact of microplastics on the biological and chemical treatment processes in bioretention. It is known that microplastics in soil affect their physical and chemical properties and biological processes including microbial communities and plant growth (Xu et al., 2020; Zhang et al., 2021). These effects may have an impact on water quality treatment in bioretention but have as yet not been assessed in research. But given that microplastics likely occur in the vast majority of bioretention field sites, these effects have been included in these studies, although not specifically quantified.

The finding that large percentages of stormwater pollutants are trapped in the top layer of bioretention facilities has implications for bioretention maintenance. When maintenance of the filter is needed due to high pollutant concentrations and/or clogging, simply replacing the top layer may often be sufficient to restore the entire filter’s performance. Similar guidance has been suggested concerning heavy metals and a number of organic pollutants (e.g. Al-Ameri et al., 2018; Blecken et al., 2011; Tedoldi et al., 2017; Furén et al., 2022). This study confirms the suitability of this approach for microplastics. The excavated, polluted filter material may be characterized as (hazardous) waste and has to be handled accordingly. This is dependent on (inter alia) pollutant concentrations and relevant guideline target values, as e.g. discussed for organic micropollutants by Furén et al. (2022). Corresponding guidelines defining microplastic concentrations in soil or sediment are (to the best knowledge of the authors) not yet available.

Although microplastics appear to accumulate in the top media layers, the microplastics’ fate in the facilities cannot be fully determined by this study. Hypothetically, the microplastics can be fragmented into smaller micro or nano plastics, falling outside the applied detection size range (lower limit corresponding to 40 μm). Due to their smaller size, these particles may be transported through the filter media with the infiltrating water. Fragmentation of plastics can be caused by e.g. photo, biological, and mechanical degradation (Yousif and Haddad, 2013). Oxidation due to UV radiation, which may take place at the filter face, results in reduced elasticity and makes plastic brittle and breakable (Song et al., 2017; Yousif and Haddad, 2013). Plastic litter of e.g., PP, PS and PET has been shown to continuously degrade to smaller particles due to UV exposure in laboratory tests (e.g. Oborn et al., 2022; Lambart and Wagner, 2016). Species of e.g. fungi, bacteria and algae has been shown to break down microplastics in laboratory studies (Bacha et al., 2023) and, freeze and thaw processes (Koutnik et al., 2022b), as well as water abrasion (Ravishankar et al., 2018) cause tension in the plastics and may contribute to enhanced fragmentation and downward mobility. For instance, Ren et al. (2021) conclude in a review on microplastics in the soil-groundwater environment that transport of aged microplastics into the groundwater can occur due to enhanced mobility. Given that bioretention can be designed to exfiltrate the treated water (instead of discharging it through an underdrain), migration of microplastics from bioretention to groundwater seems conceivable.

6. Conclusion

The results of this study on concentrations, distributions, and composition of microplastic particles in nine bioretention systems aged 7–12 years suggest that:

1. PP, EVA, PS and EPDM rubber are the most abundant polymer types trapped in the filter media of bioretention systems;
2. Large percentages of microplastic particles are black particles: both non-black and black particles were observed in 28 of 33 samples (median percentage of black particles: 39%), highlighting the importance of analytical methods in characterizing microplastics;
3. Distance to the inlet does not significantly affect the accumulation of microplastic particles in surface layers (0–5 cm) of the filter media;
microplastics preferentially accumulate on the surface layers of bioretention filter media.

Further studies on microplastics in bioretention systems should include analyses of smaller size fractions and more detailed characterization of plastic particles in terms of size, density and form. In addition, factors such as vegetation and freezing of filter media should be included in further field experiments to study their effects on microplastic distributions in filter media, and analytical methods should be applied that can provide quantitative estimates of black particles (e.g., tire and road wear particles).

Author contribution

Katharina Lange: Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Robert Furen: Conceptualization, Methodology, Validation, Investigation, Writing – review & editing, Helene Osterlund: Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition, Ryan Winston: Conceptualization, Methodology, Investigation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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.

Data availability

The full data set is included in the submission.

Acknowledgements

We gratefully acknowledge the financial support provided by the VINNOVA (Swedish Governmental Agency for Innovation Systems) DRIZZLE – Centre for Stormwater Management (Grant no. 2016-05176), Swedish Environmental Protection Agency through the project urban plastics (ref no. 208-0182-18) and the Stormwater&Sewers research cluster, financed by Svenskt Vatten (Swedish Water and Wastewater Association) and member partners. The authors thank all staff who supported the field and laboratory work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemosphere.2023.138103.

References


