

Modelling microplastics in bioretention systems: A review

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Abstract

Urban stormwater is both a major source and a mode of transport for microplastics in the environment. Black-box field studies have found that bioretention cells, a type of low impact development (LID), consisting mainly of engineered porous media, are effective systems for capturing microplastics. However, the mechanisms of how microplastics are transported, removed from stormwater, and fragmented within bioretention cells are unclear. Additionally, the impacts of microplastics on the hydrology and microplastic removal performance of bioretention cells remain unclear. This study assesses the ability of existing stormwater engineering tools to model microplastic removal using LID and reviews the literature on the mechanisms of microplastic filtration in porous media. None of the evaluated stormwater tools were found to be well-suited to model microplastic removal via bioretention. We identified 74 studies that, at times, misinterpreted “all microplastics” as colloids. We recommend using a combination of two models to evaluate the full spectrum of microplastic sizes. Currently, the best-suited models are HYDRUS and the cake-layer model described in Li and Davis (2008a), which can be adapted for this purpose. More column studies are needed to parametrize these models that use the full range of polymer types and morphologies of urban stormwater microplastics.

Keywords: Stormwater management, transport, pathways, fate, colloids, filter

1.0 Introduction

Bioretention cells, a type of low impact development (LID), consist of depressions filled with engineered porous media covered with mulch and vegetation (Roy-Poirier et al., 2010). They can effectively remove both total suspended solids (TSS) (Li and Davis, 2008b; Nazarpour et al., 2023) and microplastics from stormwater (Boni et al., 2022; Gilbreath et al., 2019a; Johansson et al., 2024; Lange et al., 2022b, 2021a; Liu et al., 2020; Smyth et al., 2024, 2021a; Werbowski et al., 2021a). Microplastics (MPs) are plastic particles in the size range of 1 μm to 5 mm in any dimension (Napper and Thompson, 2020). Previous studies of total suspended solids and microplastics remove from stormwater have relied on a black-box approach where inlet and outlet concentrations are determined, from which a percent concentration decrease (often referred to as “removal”) is calculated. This black-box method offers useful information about a bioretention cell’s contaminant removal capacity; however, it does not examine what happens inside the bioretention cell.

Although microplastics are suspended particles within stormwater their concentration and removal rates provided by infiltration-based systems, like bioretention cells, are not necessarily equivalent to removal rates for total suspended sediments (TSS). Sprakman et al. (2020b) and Smyth et al. (2021) reported different removal rates for TSS (63%) and microplastics (84% for the 106 to 5,000 μm size fraction) for a bioretention cell in Vaughan, Ontario. Microplastics in the latter study consisted largely of microfibers (79%), rubbery particles (17%) and fragments and films making up the rest of the morphology distribution in stormwater runoff entering the cell (Smyth et al., 2021a). The morphology of microplastics, particularly microfibers, are drastically different from other forms of suspended particulates like sand (spherical), silt (spherical) and clay (plate-shaped) (F. Li et al., 2024a; Rowell, 2014). Consequently, models developed primarily to model conventional stormwater TSS may not necessarily describe the filtration processes of microplastics. Figure 1 illustrates various transport processes within porous media that impact the vertical transport of microplastics.

Field studies are critical to provide performance data under real conditions. However, they are resource-intensive and field-derived results are dependent on site-specific characteristics. Modelling can act as a useful complementary tool to overcome site-specific limitations and investigate broader questions than field studies. Both black-box and mechanistic models can be employed in models. Model duration can vary from short-term and event-based to long-term and continuous. Modelling can allow for different spatial scales to be tested.

Practitioners and regulators rely on engineering tools, in particular stormwater models, for various reasons as follows when evaluating low impact development (LID) systems (Eskandaripour et al., 2023; Nguyen et al., 2023). Environmental government agencies throughout North America require or specify desired TSS removal criteria for urban stormwater, stormwater treatment, retention and detention volumes, and maximum runoff or discharge flow rates. Stormwater models are essential tools to size and design LID systems and to evaluate the efficiency of LID applications with respect to project goals and/or regulations (Shahrokh Hamedani et al., 2023). Models are also used to optimize LID application performance such as improving runoff water quality, decreasing runoff volume, and decreasing the implementation costs of LID by selecting the optimal location and type (Shahrokh Hamedani et al., 2023). Finally, stormwater models can be used in more recent applications to evaluate LID effectiveness in moderating the impacts of climate change scenarios on surface runoff in urban areas (Ghodsi et al., 2020).

Spraakman and Rodgers et al. (2020a) identified thirty-five numerical models used to evaluate contaminant transport and fate in a bioretention cell and/or its catchment. Of these, twelve (or 35%) of the identified models were used to model suspended solids, including SWMM, MUSIC, HSPF-BMP, WinSLAMM, and four single-use models. Additional models identified in Sprakman and Rodgers et al. (2020a) and addressing water quality in bioretention cells include HYDRUS, MPiRE, Quinn and Dussailant (2014) and twelve other single-use models. We found two additional models used for the evaluation of TSS removal with a bioretention system, SUSTAIN and SAMF, (as of August 9, 2024), which we added to this review.

Quantity and quality stormwater models can be classified as either deterministic (i.e., always produce same results for one set of inputs) or probabilistic (i.e., stochastic; produce different results for the same inputs due to incorporated uncertainty) or hybrid (i.e., a combination of both) (Obropta and Kardos, 2007). Many well-known urban hydrology models use deterministic models such as

SWMM, HSPF, and MIKE URBAN (Assaf et al., 2024; Obropta and Kardos, 2007); whereas, MUSIC is a stochastic model (Imteaz et al., 2013a). There is rapid development and increased use of Artificial Intelligence (AI) and within it, Machine Learning (ML), in many fields including flood management, as it can be used to proficiently manage large datasets, identify patterns, and determine optimal solutions through machine learning (Berment and Bilmes, 2024). Recently, there is interest on their use to model urban stormwater (Li et al., 2024).

The objectives of this review are: 1) to determine the pathways and equations that govern the observed concentration decreases hereafter referred to as the removal of microplastics in porous media, 2) to evaluate existing stormwater catchment and low impact development models for their capacity to model microplastics transport, fate, and removal efficiency, and 3) to provide recommendations for the adaptation of engineering tools and to their users to appropriately model microplastic removal with bioretention systems.

2.0 Methods

A systematic review of the literature on microplastic filtration in porous media, outlined in Figure 2, was completed. Two-hundred and seventy-four articles were identified on July 11, 2024 after duplicate removal using the following search terms in Engineering Village and Scopus: “microplastic AND porous media”, “filtration and microplastic* and media”, “filtration and microplastic* and porous”, “filtration and microplastic* and porous media”, and “filtration mechanism* and microplastic* and porous media.” An additional twelve articles were identified that were not returned in Engineering Village from these searches.

Elimination criteria used to exclude articles was as follows:

- The article was not available in English.
- The work was not a peer-reviewed journal article and/or it was not available (i.e., conference presentation/poster, other presentation, patent application).
- The topic was significantly outside the project scope (i.e., metal alloys, deformation of porous rock, imaging methods with X-ray tomography, acoustics, etc.).
- Filtration in porous media was discussed and/or microplastics were characterized, often in the context of drinking water treatment, however no specifics on filtration mechanisms or equations

were outlined. Other excluded topics included air filters/biochar performance, groundwater characterization, and microplastic aging.

- Development or optimization of microplastics methods for sample processing and/or quantification and identification analysis broadly.
- Filtration of microplastics via drinking water treatment technologies (e.g., glass fiber microfiltration membrane, series of steel filters, etc.) and not porous media was evaluated.
- The study concluded that results may have implications for microplastic transport, but filtration mechanisms (e.g., filtration theory mechanisms including interception, sedimentation, or diffusion or attraction/repulsion energies between particles) were not discussed in the article.
- The focus of the study was microplastic-assisted transport (i.e., vectors) of chemicals, not microplastics themselves.
- The focus of the study was ecotoxicology impacts of microplastics on various organisms.
- The study evaluated horizontal streambed transport of microplastics and not vertical transport.
- The article discussed colloid particle filtration either not specific to microplastics or with reference to microplastics, but without discussion of specific filtration mechanisms.
- Some impacts of microplastic presence on soil (e.g., soil structure, porosity, etc.) were evaluated, but the transport of microplastics was not studied.
- Only nanoplastics were studied, i.e., plastics below 1 μm in size.

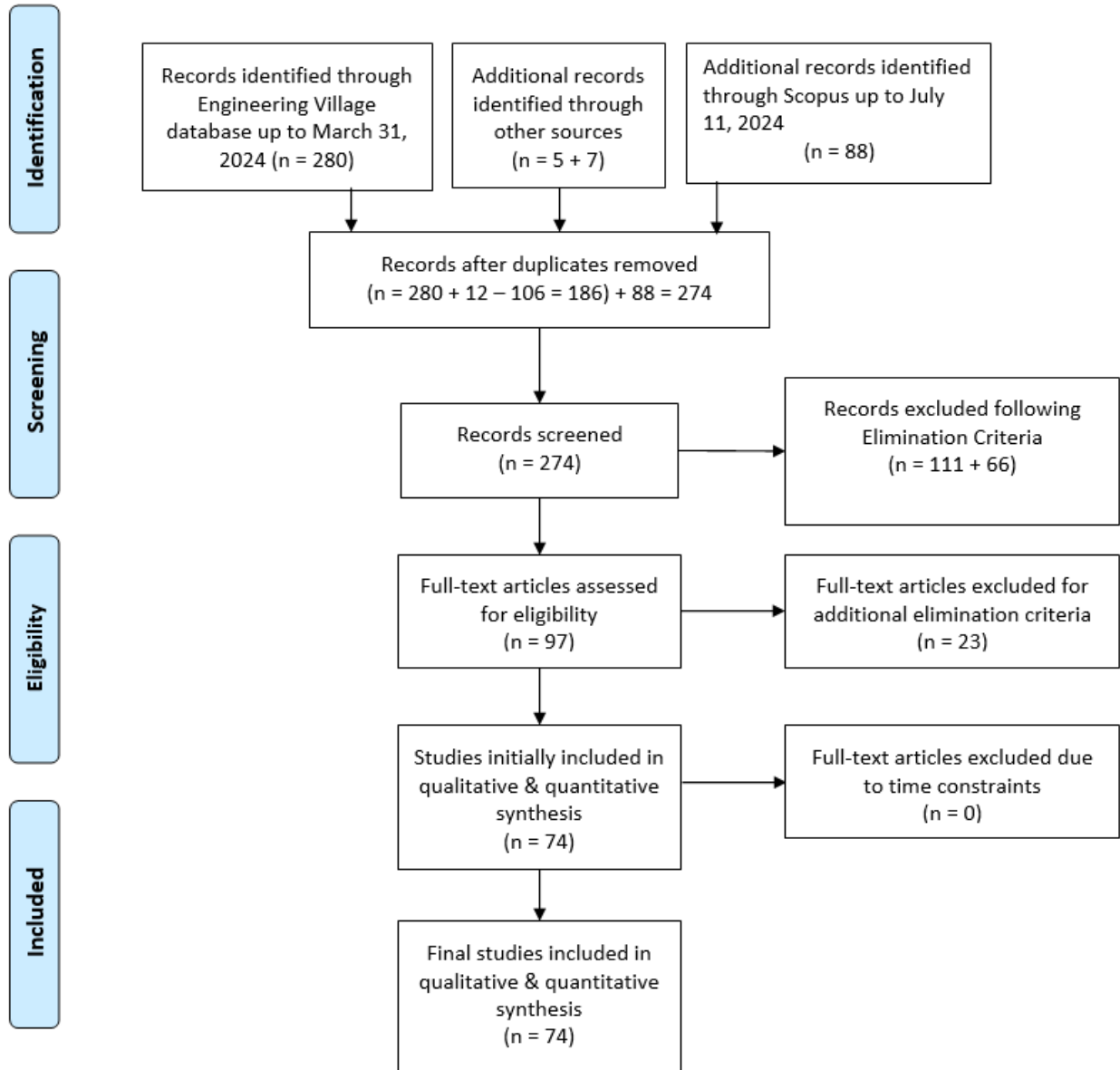


Figure 2. Systematic literature review process

Following eligibility screening, seventy-four articles were identified for synthesis; the majority (fifty-five papers or 74 %) were soil media column studies (Figure 3). An additional six studies provide numerical models of microplastic transport in porous media, of which three studies also include soil media column studies. Six review papers summarized microplastics in porous media. One review summarizes microplastic studies in soil generally (O’Kelly et al., 2021) and one summarizes the impacts of UV weathering on microplastic transport in porous media (Y. Xu et al., 2024a). The other four review papers focus on microplastic transport in porous media. Two of these reviews focus on influential factors impacting the transport of microplastics (Geng et al.,

2024; F. Li et al., 2024a) and the other two reviews include sections focusing on the transport mechanisms of microplastics (Xu et al., 2023; Zeng et al., 2024). Five studies evaluate microplastic transport at the pore-scale. Additionally, there is one field study and one permeable pavement study, the latter of which discusses relevant filtration theory for porous media. Of the fifty-five soil media column studies, thirty-six studies are sand-filled columns with an additional six studies that use biochar-amended sand or soil, eleven studies describe glass bead-filled columns, one is a gravel-filled column, and one uses silica bead, sand, and gravel columns.

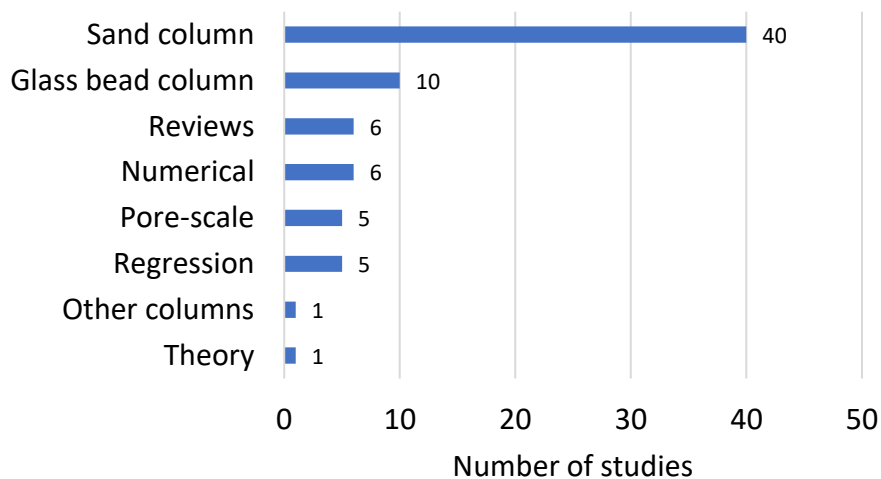


Figure 3. Study types included in the papers reviewed; where “other columns” includes a study which evaluated silica balls, sand and gravel columns.

Finally, six additional articles and one PhD thesis were identified that via field studies evaluate microplastic fate in a bioretention cell (Beaurepaire, 2024; Vera S Koutnik et al., 2022b, 2022a; Kuoppamäki et al., 2021; Lange et al., 2022a; Mbachu et al., 2022; Mengistu et al., 2022).

Parallel to the systemic literature review, a review of bioretention water quality models that address TSS transport and fate was conducted. These models are listed in Table 1 (rows 1 – 12). They include both open source and commercial software as well as single study-derived models. Two models, MPiRE and Quinn and Dussailant (2014) were excluded from this review as they are not publicly available and appear to be irrelevant as they did not model suspended solids. Shao et al. (2018a) which models the resuspension of settled TSS from LID systems during stormwater overflow was also excluded because the primary focus of this study was the filtration performance for incoming microplastics and not resuspension. Although Shao et al. (2018) is potentially a

relevant component when conducting a mass balance for microplastics entering and exiting a bioretention cell, this model on its own cannot be used to model microplastic concentration decrease from stormwater via bioretention. MIKE URBAN was added to this review as an additional commonly used and commercially available modelling software used for decision-making regarding stormwater and LID systems. Finally, in addition to PCSWMM, an EPA SWMM add-on tool (Tiveron et al., 2018) which is a single-use model was included in the review to model suspended solids reduction in stormwater with bioretention cells. PCSWMM uses the same computational settings as EPA SWMM, however this add-on tool was evaluated separately from PCSWMM as a unique single-use model.

Table 1. Contaminant removal principles of common stormwater LID software used to model water quality.

	Model	Type	Model Basis	LID contaminant removal	Input parameters specific to TSS removal
1	PCSWMM/ EPA SWMM¹	Open Source/ Commercial	Theoretical	Reduction of runoff contaminant load equivalent to reduction in runoff flow volume.	None. (Runoff flow inlet and outlet volumes)
2	WinSLAMM²	Commercial	Empirical (American field data)	Tabulated removal rates based on biofilter soil and pore size.	Inlet TSS particle size distribution and filter media (i.e., soil) type category.
3	MUSIC³	Commercial	Theoretical flow & Empirical water quality (lab study)	Tabulated removal rates (TSS, TN & TP) based on lab study. Can “swap a pollutant” to enter user-defined removal rate for any pollutant.	Filter media category and presence of vegetation, exfiltration, submerged zone and/or underdrain.
4	HSPF – BMP⁴	Open Source	Theoretical	Tabulated theoretical	Inlet concentration of pollutant and decay

				formulas for various pollutants.	amount (expressed as concentration/interval)
5	MIKE URBAN	Commercial	Theoretical	Coupled with equation solver to enter user-defined water quality treatment processes.	For sediment removal: Fall velocity, inlet flow rate, node (i.e., bioretention) surface area, turbulence constant indicating settling performance
6	HYDRUS⁵	Open Source (1D)/ Commercial	Theoretical	LID not built-in. Models solute transport and removal. Particles: filtration theory.	Soil transport parameters (e.g., bulk density, etc.), ** solute 1 (i.e., colloids) specific transport parameters (e.g., molecular diffusion and diameter of soil grains), and solute reaction parameters (e.g., blocking function for 2 nd sorption sites, etc.)*** Can also add parameters for any solute of interest on colloids.
7	SAMF⁶	Single Use	Theoretical	TSS removal = Difference in quantities of TSS obtained by multiplying TSS concentrations and SWMM-simulated runoff volumes	TSS concentration (and simulated inlet and outlet runoff volumes)
8	SUSTAIN⁷	Single Use	Theoretical	First order decay, Kadlec and Knight's k'-C'* method	(Inflow rate times series), TSS concentration time series, settling velocity for TSS particles
9	Li and Davis, 2008	Single Use	Theoretical	TSS removal = Surface	Depth of soil, cross-sectional area,

				cake filtration + depthwise filtration	hydraulic conductivity, density of TSS, input flow rate, TSS concentration as a function of time.
10	GIFMod⁸	Single Use	Theoretical	Models solute transport and removal. Particles: filtration theory.	Soil transport parameters (e.g., bulk density, etc.), ** solute 1 (i.e., colloids) specific transport parameters (e.g., molecular diffusion and diameter of soil grains), and solute reaction parameters (e.g., blocking function for 2 nd sorption sites, etc.)***
11	L-THIA⁹	Single Use	Theoretical	Reduction of runoff contaminant load equivalent to reduction in runoff flow volume.	None. (Runoff flow inlet and outlet volumes)
12	Tiveron, Gholamreza-Kashi and Joksimovic, 2018	Single Use	Theoretical	Single collector model for TSS (Yao et al., 1971)	Influent TSS concentration, filter bed porosity, bed depth, filter bed collector diameter, fluid viscosity, TSS particle diameter(s), velocity of fluid, TSS and filter bed particle densities.

Acronyms: United States Environmental Protection Agency (EPA)/ Personal computer (PC) version of the Storm Water Management Model¹, Source loading and management model: An urban area nonpoint source water-quality model for Wisconsin², Model for Urban Software Improvement Conceptualisation³, Hydrological Simulation Program-Fortran – Best Management Practices⁴, HYDRUS is not an acronym⁵, Sustainable Assessment Model Framework⁶, System for Urban Stormwater Treatment and Analysis Integration⁷, Green Infrastructure Flexible Model⁸, Long term hydrologic impact analysis.⁹ *For simulating first order decay, as done by Ackerman and Stein (2008) for total suspended solids and copper. **Longitudinal dispersivity, fraction of sorption sites in equilibrium with soil solution, and immobile water content. ***First-order attachment coefficient for first and second sorption sites, first-order detachment coefficient for first and second sorption sites, blocking function for 1st sorption sites.

3.0 Results and Discussion

3.1 Microplastic transport in porous media: Literature review

3.1.1 Evaluated microplastic characteristics to date

Figure 4 gives an overview of the microplastic characteristics (i.e., shape, polymer type, and size fraction) evaluated in transport column studies to date. Some studies evaluated a single combination of microplastic characteristics (e.g., polystyrene spheres between 1 – 10 μm); whereas, other studies evaluated multiple combinations of characteristics in the same study. For example, Waldschläger and Schüttrumpf, (2020) used seven different polymer types of four different shapes, all in particle sizes larger than 500 μm .

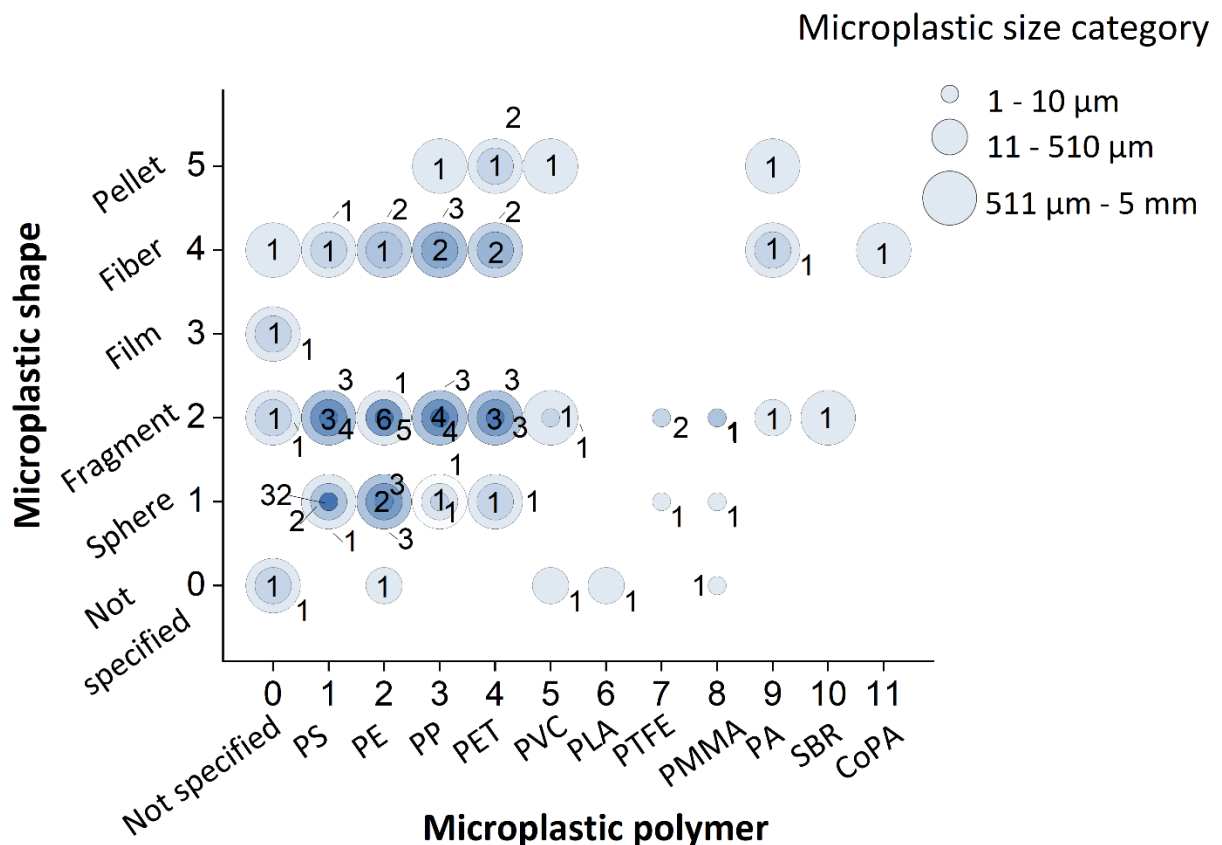


Figure 4. Microplastic characteristics evaluated in soil media column studies, where the numbers indicate the quantity of studies. PS: polystyrene, PE: polyethylene, PP: polypropylene, PET: polyethylene terephthalate, PVC: polyvinyl chloride, PLA: polylactic acid, PTFE:

polytetrafluoroethylene, PMMA: poly(methyl methacrylate), PA: polyamide, SBR: styrene-butadiene rubber, and CoPA: co-polymer of Nylon 6 and Nylon 6,6.

The most commonly used microplastic shape and polymer in column studies are polystyrene spheres in the 1 – 10 μm range (32 studies, 63% of column studies). Polystyrene spheres, by themselves, are not a good surrogate to assess the transport of all microplastic polymer particles in porous media. For microplastic porous media transport studies, it is essential to evaluate the full array of plastic types found in stormwater that could be expected to enter bioretention cells or other porous infiltration systems in the environment. Polystyrene is hydrophobic in nature, which leads to the self-agglomeration of polystyrene particles and, therefore, aids in the filtration of these larger particle clumps (Subair et al., 2024a). However, polarity and material density vary significantly between plastic types, and these two characteristics, among others, play important roles in microplastic mobility in porous media (Dong et al., 2024).

Additionally, of the included polystyrene-focused articles, 20/35 studies (57%) used carboxyl- or amine-modified polystyrene spheres versus polystyrene particles with non-modified surface functional groups. These carboxyl and amine-modified particles are commonly used for specific applications in biomedical and diagnostic fields as their surface modification improves colloidal stability and prevents particle aggregation (Panagiotidis et al., 2023; Zhang et al., 2018), thereby changing the way these particles can be transported in porous media. In stormwater, however, a wide variety of plastic polymers exist, which are dominated by polypropylene and polyethylene (Smyth et al., 2021a).

3.1.2 Definitions of microplastics and colloids

There is no one strict definition of colloids that helps distinguish them from larger particles as the term colloid has variable definitions (Molnar et al., 2019). Based on combined definitions of size, colloids mainly refer to particles with diameters in the 0.001 – 10 μm size range (Baalousha et al., 2009; McCarthy and McKay, 2004). Typically, microplastics are defined as plastic particles between 1 – 5,000 μm , although there is some variability in this term as well. Microplastics therefore only overlap with a small proportion of colloids. Additionally, microfibrils, thin and long rod-shaped microplastics can potentially meet a definition of colloids if their diameters are less than 10 μm . Microfibrils can, however, reach up to several millimeters in length, so it is unclear if they act like colloids at these lengths.

Due to differing size definitions, it can be more useful to define colloids based on other physical characteristics, which influence their transport behaviour. In particular, compared to larger particles, colloids experience “greater rates of Brownian motion, higher reactivity because of their higher surface areas, and greater influence under short-range surface forces” (Molnar et al., 2019). They can be defined as large enough to hold an electrical surface charge and small enough to remain in the water column for sufficient timeframes and for aggregation to dominate over single-particle transport (Baalousha et al., 2009). Based on these definitions, colloidal microplastics can potentially include microfibers with diameters less than 10 μm and can include microplastics of other morphologies such as fragments, films, spheres, etc., between 1 to 10 μm in diameter that also have other colloidal physical characteristics.

There is variable use of the term “colloid” and its definition in the included studies (Figure 5). Of the 74 articles reviewed in this study (Table S2), 59 articles refer to colloids, of which 47/59 articles studied microplastics smaller than 10 μm and, therefore, in the possible range of colloidal microplastic particles. However, only six of these articles explicitly define colloids. The lack of explicit definitions of colloids and the use of colloidal theories (e.g., DLVO theory) to evaluate the transport of microplastics causes confusion around the characteristics of microplastics being evaluated and the extent to which different microplastics can be considered as colloids and modelled as such. Three articles (Gao et al., 2021; O’Connor et al., 2019; Xu et al., 2023) distinguish between the larger size of microplastics compared to colloids and point out the importance of questioning the extent to which microplastic particles behave like colloids. There is a lack of information on whether microplastics or some subfractions behave like colloids and if this varies with microplastic sizes and morphologies.

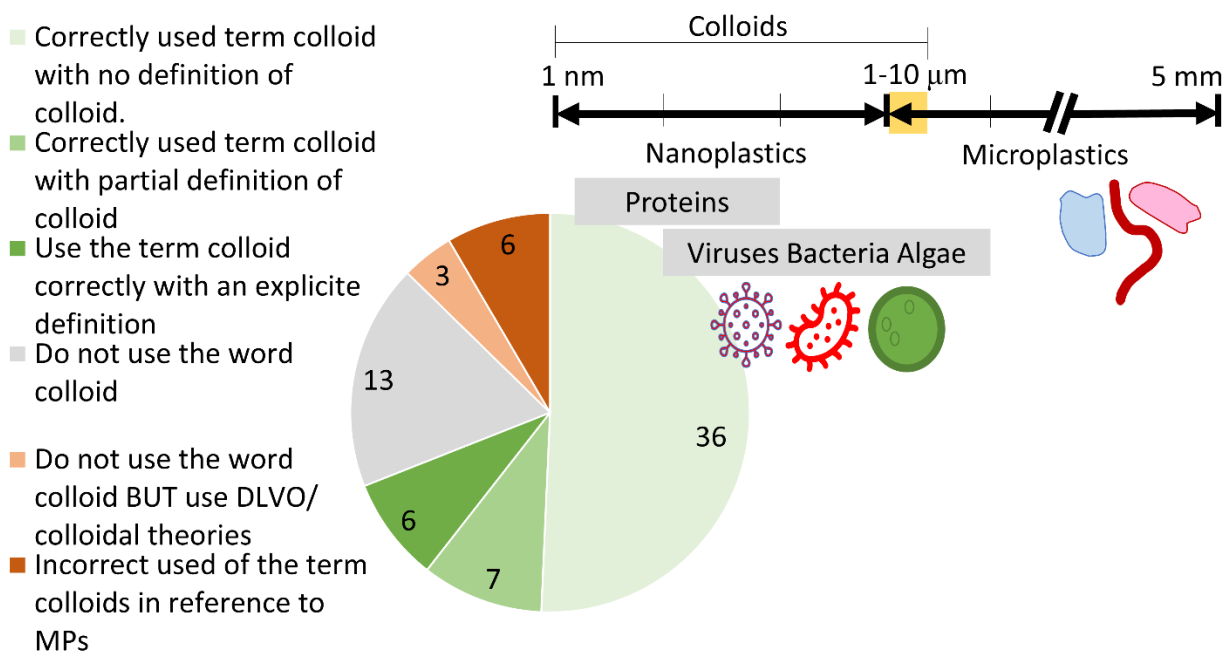


Figure 5. Usage of the term “colloid” in the studies included in this review

More studies are needed that focus on larger non-colloidal microplastics (i.e., microplastics larger than 10 μm). Future transport studies should characterize and report the physical characteristics of the microplastics they study, and they should be careful to distinguish between colloidal and non-colloidal MPs. Further, they should state their definition of colloids in reference to microplastics that they use.

3.1.3 Colloidal microplastic soil media column studies

There is a lack of microplastic studies focusing on transport in porous media that systematically investigate the qualitative and quantitative transport mechanisms of microplastics (Geng et al., 2024; Xu et al., 2023; Zeng et al., 2024). A number of microplastic vertical transport studies ($n = 49$, of which 5 are reviews) exist on colloidal-sized microplastics, in the size range of 1 – 10 μm . These microplastic colloid studies explain their transport with one of two theoretical methods: either clean bed filtration theory (CFT) or a version of DLVO (Derjaguin–Landau–Verwey–Overbeek) theory, explained briefly in the Supporting Information (SI) Section S1 and in detail elsewhere (Xu et al., 2023). Many of these colloidal studies also evaluate empirical transport models using advection-dispersion theory and obtain breakthrough and/or retention curves from which model parameters for particle deposition and remobilization rates can be obtained (Xu et

al., 2023). Of these 35 studies, most are column experiments which measure breakthrough curves, simulate them with different equations such as the advection-dispersion equation and/or apply DVLO or XDLVO (i.e., extended DLVO theory) theories to qualitatively understand the impact of different factors on the transport of microplastics in porous media. DLVO and XDLVO theories are used specifically to calculate interaction energies between microplastic-microplastic and microplastic-porous media particles (Feng et al., 2022). These studies, however, do not look at the full range of potential transport mechanisms relevant to microplastic transport, but rather employ a single theory and/or empirical study.

We suspect that microplastics are thought to be removed like total suspended solids in porous media by physical processes, including surface caking and depth-wise filtration (Li and Davis, 2008a). Conversely, colloids have known deposition mechanisms in porous media including interception, sedimentation, and diffusion (Baalousha et al., 2009). These physical removal mechanisms are influenced by the particles' characteristics, namely microplastic particle size, surface charge, aggregation state, shape, and density, which vary with polymer type (Baalousha et al., 2009).

Beyond these main physical processes, other factors can also influence microplastic removal from stormwater in bioretention cells. These could include microplastic ingestion and excretion by biological organisms in bioretention soil (Chang et al., 2022), flow short-circuiting via macropore structures created from root decay, earthworms and freeze-thaw cycles in cold climates (Ding et al., 2019; Nichols et al., 2021) and microplastic resuspension after initial settling at the surface of LID spilling out via overflow structures (Shao et al., 2018). Further, microplastics can decrease in size over time due to photodegradation (Tuttle et al., 2024) and they are also known to fragment into smaller pieces over time from mechanical stresses, solar radiation and organism ingestion and excretion (Alimi et al., 2022). Aggregation of microplastics could influence their removal in porous media systems. It is known that tire and road wear particles can be transported as aggregates (Zhu et al., 2024). Some microplastics, such as polystyrene, are also known to self-agglomerate and can be transported and filtered out as aggregates (Subair et al., 2024a). Microplastics can also form and be transported as aggregates with natural material like clay particles (Xu et al., 2023). Changes in microplastic particle size over time could influence their retention in porous media, as their size affects the relevant physical processes governing their transport. Finally, some microplastics can be slowly weathered under specific environmental conditions (e.g., presence of

specific microbes, appropriate moisture content, temperature and other conditions that promote desired microbial growth) (Miri et al., 2022).

The included colloidal microplastic transport studies also include several articles on the co-transport of microplastics and different soluble chemicals. They look at how varying concentrations of co-existing contaminants impact the transport of microplastics. Chemicals evaluated include surfactants (Jiang et al., 2022; Sun et al., 2022), possible co-contaminants like nonylphenol, an endocrine disruptor (Xu et al., 2022), and salt (Feng et al., 2022; Hou et al., 2022). Two column studies (Feng et al., 2022; Hou et al., 2022), which examine the impact of salt on microplastic transport, are intended to examine microplastic transport in seawater sediments, where the seawater used in the studies is artificially made. However, these studies are also relevant in a bioretention context, as high sodium levels can be found in stormwater runoff in cold climates where salting is used to increase traction between pavement and vehicle tires and/or pedestrians.

Studies also investigate the impact of other key factors, including porewater chemistry (e.g., organic carbon/humic acid, ionic strength) on microplastic transport in porous media. They examine the impact of microplastic characteristics (i.e., surface roughness, size, density, aging, surface modifications) (M. Zhang et al., 2024), porous media characteristics (e.g., sand particle distribution sizes), wet-dry cycles (Ranjan et al., 2023) and flow rate (Feng et al., 2022) on microplastic vertical transport.

All these factors impact the extent of vertical microplastic transport. This makes it difficult to estimate microplastic vertical transportation depth in porous media, as there can be large variations in each of these factors from one site to another. For example, the physical characteristics of all microplastics types vary in their pristine state from different fabrication methods. These can also change over time due to aging via UV exposure, i.e., shrinking in size, and also minimally from microplastic fragmentation (Feng et al., 2022; Tuttle et al., 2024). Additional factors that can impact microplastic transport in porous media include biofilm formation on microplastics, the aggregation of microplastics with phytoplankton, and surface roughness of substrate that were not considered in Feng et al., (2022).

3.1.4 Modeling studies: Literature Review

Of the five numerical models identified in this literature review, two complex models are developed at the pore scale (Engdahl, 2018; Johnson, 2020). These models are useful to understand microplastic transport mechanisms in soil pores. However, directly extrapolating these fine-scale processes to those observed in a full-size bioretention cell is not possible. More modelling studies are needed to evaluate the transport and fate of microplastics in full-scale bioretention cells. The other three more recent and complex numerical models (Guo and Fei, 2023; Lim et al., 2023; Ryu et al., 2021) use advection-dispersion and attachment-detachment models to model the vertical transport of microplastics in porous media. They determine model parameter coefficients that can be used in HYDRUS 1D for very specific experimental conditions, but more work is needed to predict the porous media penetration depth of microplastics in different soils/sediments and media conditions. Further, Ryu et al. (2021) does not take microplastic size into account in transport modelling, thus overlooking this important factor in predicting their vertical transport.

Five studies created simplistic regression models to predict the soil penetration depth of microplastics from the number of wet-dry cycles, the morphology or size of microplastics, and/or size of collector particles/grains (e.g., soil, sand, etc.) (Gao et al., 2021; Vera S Koutnik et al., 2022b; Mancini et al., 2023; O'Connor et al., 2019; Waldschläger and Schüttrumpf, 2020a). None of these studies directly refer to microplastics as colloids. They can be used to inform microplastic sediment sampling practices and estimate the potential for microplastic entry into groundwater or underlying infrastructure in LID. However, these simplified models are limited as they lack any reference to time beyond the number of wet-dry cycles, disregard the variation in different rainfall events in terms of other hydrologic factors like rain intensity, and do not provide any information regarding clogging of soil over time. As a result, they cannot inform soil maintenance practices for bioretention cells.

Further, only two studies evaluated microfiber transport in porous media (Lüscher and Jo, 2022; Waldschläger and Schüttrumpf, 2020a). Of these, one study used fishing line to manufacture microfibers (Lüscher and Jo, 2022). Since fishing line is thick in width, it is likely not representative of textile fibers, which are more likely to be found in urban stormwater than those derived from fishing line. Thick fibers derived from fishing line versus textiles with differences in fiber width and ability to hold electrical charges might also lead to differences in fiber aggregation and whether fibers are found as single strands or in bundles in the environment.

3.2 Microplastics fate in bioretention porous media: Existing studies

Limited field-study information is available on microplastic distribution within bioretention soil media (Table S5). Currently, five field studies on this topic exist where one examines only horizontal distributions (Mbachu et al., 2022) and four examine vertical distributions of microplastics in bioretention soil media including one study that examines both (Beaurepaire, 2024; Vera S Koutnik et al., 2022b; Lange et al., 2022a; Mengistu et al., 2022). All four vertical transport studies found the greatest quantities of microplastics in the surface soil, i.e., the top five centimeters (Mengistu et al., 2022; Beaurepaire, 2024; Lange et al., 2022a) or the top two centimeters compared to deeper soil depths. Koutnik et al. (2022b) was the only study to relate microplastic concentration to depth with an exponential trend, i.e., $\ln(C) = 4.32 - 0.13z$ where z is depth and C is microplastic concentration. However, this identified trend was not related to time. Further, each of these studies used different analysis methods, resulting in different microplastic sizes and types analyzed, making results very difficult to compare.

These four studies provide valuable data that can be used to look for trends in microplastic distributions as well as Koutnik et al. (2022b)'s exponential concentration trend with soil depth. However, it is important that future studies measure these parameters in addition to time elapsed, so that microplastic distribution can be modelled over time to examine their build-up and maintenance timelines in green infrastructure which involves porous media. Also, Koutnik et al. (2022b) does not identify polymer types or morphologies which are expected to impact microplastic transport in porous media. These parameters need to be measured in future studies to distinguish microplastic transport models for different polymer types and morphologies.

In addition to these field-based studies, two bioretention soil columns also evaluate microplastic vertical distribution in bioretention media (Vera S Koutnik et al., 2022a; Kuoppamäki et al., 2021). Kuoppamäki et al. (2021) visually examined the vertical transport of dyed polyethylene microplastic beads in vegetated and non-vegetated biofilter columns made with five different types of filter media. They were found to travel deeper in vegetated columns to depths of 8 - 12 cm versus 4 - 5 cm in non-vegetated systems. Microplastic concentrations were not measured, and no quantitative analysis was conducted for microplastic distribution with depth. Koutnik et al. (2022a) examined polypropylene fragment vertical distribution under freeze-thaw cycles in soil and sand columns reflective of typical bioretention media. They demonstrated that freeze-thaw cycles have

a greater impact than wet-dry cycles on polypropylene microplastic mobility in porous media and that this mobility is greater in sand than in soil as expected due to the greater pore size in sand. Though the study mentions the use of both polypropylene fragments and fibers, it is suspected that these fibers were not reflective of thin textile fibers found in other bioretention stormwater studies due to their manufacturing method of polypropylene tubes sanded into smaller irregular shaped pieces.

More studies are needed to evaluate microplastic mobility in bioretention cell-relevant porous media using the full array of polymer types and morphologies found in stormwater, in particular thin flexible fibers. More quantitative studies in relation to time elapsed are needed in addition to visual observations in soil. Further the exponential trend for microplastic concentration by soil depth is reported for concentrations of microplastics per gram of soil. This requires knowledge of microplastic counts per soil mass and not microplastics counts per litre of stormwater as done in other limited bioretention microplastic studies (Gilbreath et al., 2019a; Lange et al., 2022b, 2021a; Smyth et al., 2021a; Werbowski et al., 2021a). More research is needed to convert microplastic stormwater concentrations into soil concentration estimates for bioretention cells. This conversion would allow field-tested stormwater microplastic concentrations to be used to model microplastic removal with bioretention, build-up and associated maintenance needs.

3.3 Engineering stormwater tools

Both open source and commercial engineering tools listed in Table 1 are used to evaluate contaminant removal from stormwater using low impact development systems. Numerous contaminant removal efficiencies have been modelled with these tools such as for TSS, nutrients, heavy metals, and pathogens, among others at both the catchment and bioretention system scales (Sprakman et al., 2020). Since microplastics are a type of particulate matter and form a subset of TSS, we hypothesized that bioretention TSS removal models could also be used or adapted to model microplastics removal in a bioretention cell. Table 1 outlines the general underlying principles employed to evaluate contaminant removal by the engineering tools evaluated in this study. Details on the specifics of how these models calculate the contaminant removal of low impact development systems are provided in Table S1.

None of the reviewed engineering tools are currently well-suited to model microplastics' fate in bioretention cells. In some cases, estimations of contaminant removal efficiency rely on empirical

data, which is currently very limited for microplastic filtration in porous media. In other cases, the filtration theory employed is largely inaccurate for microplastics, because microplastics encompass a wide range of sizes. The physical characteristics of stormwater-derived microplastics such as shape and density also vary greatly and are relevant in filtration modelling.

The use of specific stormwater modelling software varies regionally. For example, PC SWMM and WinSLAMM are more commonly used in North America whereas, MUSIC is more common in Oceania. The selected software also depends on whether the user has a commercial licence or relies on open-source software. Since the underlying principles behind TSS contaminant removal vary between software (Table 1), the results for TSS and therefore microplastics removal estimates will vary between users based on their location and/or whether they use commercial vs. open-source software. The following sections provide more details on each engineering tool.

3.3.1 Approaches to modelling contaminant removal in stormwater tools

The reviewed engineering tools employ a variety of approaches to simulate contaminant removal provided by LID, ranging from simplistic to complex approaches. In the SWMM engine models (PCSWMM and EPA SWMM), contaminant mass reductions rely entirely on volume reductions (Rossman, 2015). This approach assumes that contaminants in bioretention cells are only affected by flow paths thus ignoring the potential influence of physical, chemical, and biological processes on contaminant fate. Likewise, two additional models, L-THIA or Long-Term Hydrologic Impact Assessment-LID and SAMF oversimplify and equate the water quality performance of LID to the change in runoff volume (Liu et al., 2015a; F. Zhang et al., 2024).

Others, like WinSLAMM and MUSIC rely on field and laboratory empirical data, respectively, to predict contaminant removal efficiencies in bioretention cells. Given the limited bioretention-specific microplastic filtration data, WinSLAMM and MUSIC lack sufficient empirical data to predict microplastic removal in bioretention cells for all microplastic types and bioretention designs.

In HSPF-BMP, a module within the HSPF software, “modellers can use recommended removal fractions [based on certain studies] pertaining to assumed BMPs” (Xie et al., 2015). The user manual lists a variety of formulas for various pollutants (Johanson et al., 1980)(example in Section S1). SUSTAIN models pollutant removal in bioretention using the first-order decay principle,

using a linear decline in the pollutant of interest (Lai et al., 2007). In the case of MIKE URBAN, the advection-dispersion model is used to calculate the transport of dissolved or suspended contaminants (i.e., materials are conserved or follow a linear decay) (DHI, 2020). LID contaminant removal can also be customized to the contaminant of interest by inputting its relevant removal mechanism parameters and equations into the software-coupled equation solver, MIKE ECO Lab (DHI, 2020). Instead of empirical tabulated removal efficiencies, this software requires the input of a user-defined contaminant removal equation and its relevant parameter values (Section S1). Information on microplastics is lacking to define the removal of microplastics from stormwater via bioretention using HSPF-BMP, SUSTAIN, and MIKE Urban. To use these models for evaluating microplastic removal with LID, an equation that governs microplastic removal is required. For example, the selected model could assume first-order decay and it would require the decay rate for microplastic removal. However, there is no one specific transport equation for microplastic removal in bioretention cells, and this removal likely varies significantly from site to site with microplastic particle sizes and types and bioretention soil media parameters.

Of the single-use studies in Table 1 previously used to model TSS removal via bioretention, only Li and Davis (2008a) is applicable for modelling microplastics. This model incorporates two mechanisms for TSS removal in bioretention porous media including depth filtration and surface cake filtration (Li and Davis, 2008a). Unlike HYDRUS, this model includes both surface and depth filtration. This model also has no size limitations for the TSS being modelled making it a more suitable candidate for modelling microplastics in a bioretention cell. The limitations of this model for microplastics modelling are that it requires microplastic column studies to inform model parameters and that microplastic concentrations must be measured as a function of time.

3.3.2 Detailed water quality models for colloids

HYDRUS is the most developed of the evaluated engineering tools for water quality modelling and it has previously been used to model various water quality parameters for bioretention cells (Li et al., 2018). Unlike the other models evaluated, it has a wide variety of built-in processes for water quality treatment. This includes particle filtration of colloids in the “C-Ride Module for HYDRUS-1D,” which requires the input of soil characteristics like the soil diameter among others, and contaminant-specific characteristics, including blocking, sticking efficiency and detachment coefficients for first and second sorption sites (Šimůnek et al., 2015a). Similarly, the integrated

EPA SWMM add-on tool (Tiveron et al., 2018) and GIFMod (also called Green Infrastructure Flexible Model) use the same colloid filtration theories as those used in HYDRUS (Massoudieh et al., 2017; Massoudieh and Aflaki, 2017). Since microplastics largely are not colloids, HYDRUS, and other models solely based the colloidal theory, are therefore likely unsuitable to model microplastics unless the model is focused on microplastics in the range of 1 – 10 μm or nanoplastics. Therefore, microplastics in the range of 10 – 75 μm are incorrectly modelled as colloids, the latter being the average upper limit of bioretention pore sizes.

The limitations of these detailed models for microplastic fate modelling in bioretention cells are twofold: 1) They can only be used to model the subsurface (i.e., particles already in the subsurface which are small enough to enter porous media) and 2) They are intended to model colloidal particles. The first limit implies that microplastic removal through surface caking is ignored. This excludes a large portion of microplastics in the model, particularly for particles larger than soil pores ranging up to those at the upper limit of the microplastic size range by its definition. For one bioretention cell with primarily sandy soil (96 – 98%), the pore size of the media ranged from 7.42 μm to 1.11 mm with an average pore size of 74.8 μm assuming soil pores are perfect spheres (Ding et al., 2019). Therefore, HYDRUS largely excludes microplastics and aggregated microplastics whose smaller dimension is around 75 μm or larger which would experience surface caking.

3.4 Engineering tool implications

Models have different purposes depending on the objectives of the project. Mechanistic models are needed to determine the fate of microplastics in porous media and the mechanisms by which microplastics are removed. These mechanistic models can be useful to optimize media design in a bioretention cell to better remove microplastics and to identify limitations of this system for different varieties of microplastics. On the other hand, black-box models could provide useful approximations in a catchment-scale study to determine optimal placement of green infrastructure or the effectiveness of treatment trains.

Based on the above definition of colloidal microplastics, we recommend using two different engineering tools. This will allow us to more accurately model the full array of microplastic sizes from a mechanistic approach, instead of a black-box method. The first one would target microfibers and microplastics less than or equal to 10 μm . Microfibers and microplastics in this category would be modelled as colloids. From the above-reviewed engineering tools, the most

suitable is HYDRUS. The second one would target microplastics greater than 10 μm , excluding microfibers. These should be modelled separately as non-colloidal particles. Our review suggests that the model by Li and Davis (2008a) would be best suited for this category.

To run these models, more refined column studies are needed to inform parameters for both HYDRUS and the Li & Davis, 2008 model. For HYDRUS, existing column studies for colloidal microplastics can be used and column studies evaluating microfibers as well as environmentally-weathered microplastics are needed. Field-relevant microplastics mixtures should be employed in soil media column studies. For the Li & Davis (2008a) model, column studies are needed with a broad array of larger than colloidal-sized microplastics, excluding microfibers. These studies are needed to determine model parameters such as the soil media filter coefficients, porosities, and hydraulic conductivities among other parameters for each of the three layers of the media in the column (i.e., defined as the surface layer, middle “working zone”, and bottom “cake layer”) (Li and Davis, 2008a).

In addition to these models, in situations where black-box models can provide useful approximations and mechanistic models are not required, existing bioretention studies on microplastic removal from stormwater can provide estimates for microplastic removal efficiencies. Based on Table S6, five bioretention field studies have evaluated the decrease in microplastics concentration from stormwater using varying analytical methods for microplastics between 20 μm to 5 mm. Based on these studies, we could approximate a microplastic concentration decrease ranging from 70 to 98 % for vegetated bioretention cells that have a 40 – 60 cm layer of porous sandy media based on current studies. In addition to field studies, two mesocosm and three lab column studies have evaluated microplastic retention in bioretention system with varied media mixes and additives (Table S6). These controlled studies have generally demonstrated high removal rates greater than 83 % for various polymers and removal rates as low as 44% for microplastics less than 500 μm in one study (Vijuksungsith et al., 2024). As a first approximation, we recommend using an 84 % \pm 11 % removal in future modeling efforts for microplastics > 20 μm . This is a similar bioretention removal rate as for total suspended solids.

Black-box models, if employing approximative microplastic removal rates, should only take values from field studies as they are more reflective of real-world conditions than controlled mesocosm and lab studies. Therefore, more field studies are needed that evaluate a wider variety

of bioretention designs including various media mixes and additives. Likewise, studies on the time to clogging, microplastic removal performance over time, and bioretention maintenance requirements for this contaminant should be conducted. We particularly recommend to conduct field studies on microplastic removal for a variety of bioretention design combinations with various soil types, vegetation, exfiltration, and underdrains. A range of microplastic size distributions should be employed in such work. This will allow tools like WinSLAMM and MUSIC to have tabulated effluent concentrations and removal rates for microplastics similar to what they currently use for other common stormwater contaminants. Caution should be used with empirical-based removal rates for contaminants, as these empirical values do not take into account site-specific conditions. In particular, the limits of lab-based rates are that they are obtained under controlled conditions and therefore not reflective of the random nature and variability of field sites.

Additionally, although this review focuses on microplastic characteristics and relevant filtration theories in porous media, another essential factor in modelling microplastic transport in this context is appropriately modelling the site-specific bioretention cell and/or porous media. A technical report evaluating green infrastructure modelling standards (Durbin et al., 2018) summarizes recommended default parameters to facilitate modelling green infrastructure systems in the absence of detailed site-specific values. Additionally, as previously discussed there are many factors regarding microplastic characteristics, substrate characteristics, and climate variables (e.g., flow rate, wet-dry cycles, and salinity). Not all of these factors are considered in current models. However, this information can be useful to make design choices for bioretention substrate based on previous column studies with key factors as discussed above. We can also qualitatively model microplastic removal by choosing low, medium or high levels of salinity, UV-exposure, substrate average pore size distribution, based on existing knowledge of the impact of these factors on certain studied microplastics.

4.0 Conclusion

The evaluated stormwater engineering tools in this review are currently not well-equipped to model microplastics removal using low impact development systems. The following recommendations are suggested to address these shortcomings:

- Two existing models should be used in combination to evaluate microplastics removal via porous media. One model such as HYDRUS should be used for colloidal microplastics

- (i.e., less than 10 μm) and another model such as Li and Davis (2008a) should be used for microplastics larger than 10 μm .
- The five existing bioretention field studies can be used to inform black-box studies, where appropriate, with an approximate microplastics removal rate of $84 \pm 11\%$ for microplastics greater than 20 μm .
 - Existing columns studies can inform HYDRUS transport parameters for colloidal microplastics.
 - More column studies are needed on fibers and whether they behave like colloids.
 - More column studies are needed to adapt a TSS model like Li and Davis (2008a) for larger non-colloidal microplastics including a wide array of polymer types, morphologies, and degrees of environmental weathering.

Acknowledgements

This research was supported by an NSERC Discovery grant and CREATE to J. Drake, an NSERC Alliance “Plastics Science for a Cleaner Future” Program ALLRP 558429 – 20 grant to E. Passeport, and a CGS-D scholarship to K. Smyth.

Supporting Information

For

Modelling microplastics in a bioretention cell: A review

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Section S1

Methods

Literature review: added details

We reviewed twenty-three articles identified by a scoping review of bioretention research (Sprakman and Rodgers et al., 2020) and from a Scopus search on August 9, 2024 for “Bioretention and TSS and Model.” Our work focused on identifying the underlying transport and fate of these models with a particular focus on the principles used to evaluate the TSS removal performance of porous Low Impact Development systems.

Section S1. Explanation of transport theories

Clean bed filtration theory (CFT)

The particle transport process is described qualitatively by the collisions between particles and a collector surface (Xu et al., 2023). The process is controlled by three main forces: interception; sedimentation; and Brownian motion (Figure S1) (Yao et al., 1971).

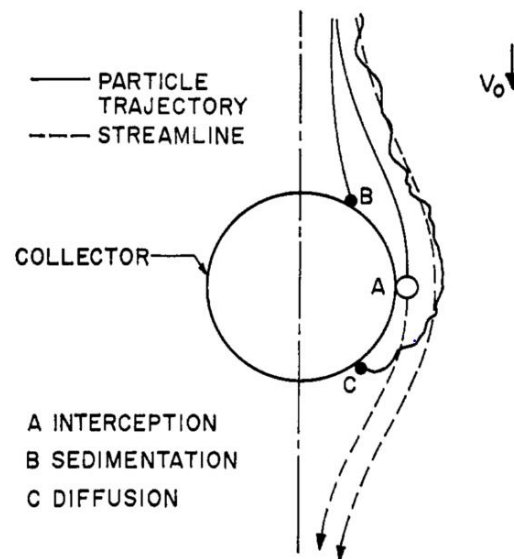


Figure S1. Basic particle transport mechanisms in water filtration (Yao et al., 1971)

Attachment efficiency (α) estimates the retainability of colloids in a porous media. It is the ratio of successful attachment collisions to total collisions and it can be determined using breakthrough curves (Xu et al., 2023; Yao et al., 1971).

$$\alpha = -\frac{2}{3} \frac{d_c}{(1-\theta)l\eta_0} \ln \frac{c}{c_0}$$

The colloid deposition rate coefficient (k) onto saturated porous media is calculated as follows (Tufenkji and Elimelech, 2004).

$$k = \frac{3(1-\theta)}{2d_c} U \alpha \eta_0$$

Where d_c : diameter of porous media (m), θ : experimental column porosity, l : effective column depth (m), η_0 : theoretical contact efficiency of q single collector, c and c_0 : colloid concentrations at column outlet and inlet respectively, and U : Darcy velocity (Tufenkji and Elimelech, 2004).

Derjaguin–Landau–Verwey–Overbeek (DLVO) theory

The attraction and repulsion energies between colloidal particles and a collector surface are described as the sum of the electrical double layer force (ϕ_{EDL}) and van der Waals force (ϕ_{vdW}). Xu et al., 2023 provides the detailed equations.

Extended Derjaguin–Landau–Verwey–Overbeek (XDLVO) theory

The total energy calculation includes electrical double layer force and van der Waals force as well as “additional interaction energies, such as Lewis acid-base, elastic; osmotic, and hydrophobic force” (Xu et al., 2023).

Table S1. Stormwater engineering tools: Details on contaminant removal methods governing modelled low impact development (LID) systems.

Model	PCSWMM	L-THIA	WinSLAMM	MUSIC	MIKE URBAN	GIFMod	HYDRUS
Company	CHI	Purdue University	PV & Associates	eWater	DHI	US EPA	PC-Progress
Country of origin	Canada	United States	United States	Australia	Denmark	United States	Czech Republic
General purpose of model	Stormwater modelling with built-in LID.	Stormwater modelling with built-in LID.	Stormwater modelling with built-in LID.	Stormwater modelling with built-in LID.	Stormwater modelling with built-in LID.	Stormwater modelling with built-in LID.	Water flow and solute transport in porous media.
Availability	Proprietary (EPASWMM is open-source)	Open-source	Proprietary	Proprietary	Proprietary	Open-source	HYDRUS 1D - open source. Other models are proprietary.
Determination of catchment runoff volume	Water Balance	Curve number based (i.e., land use, soil group, and long-term rainfall).	Based on runoff coefficients unique to land uses.	Various model options. Default: Simple Urban Runoff Model (i.e., water balance).	Various model options including four surface runoff models and one continuous hydrological model (called "MOUSE RDI").	Water balance	This model does not consider a whole catchment, but rather a specific soil column. Richard's equation governs saturated-unsaturated flow.
Model basis for contaminant removal	Theoretical	Theoretical	Empirical	Theoretical for flow. Empirical for water quality.	Theoretical	Theoretical	Theoretical

Contaminant build-up and wash off	Calculated with theoretical inputs (e.g., max build-up mass) for land uses. (Note: Land use is only used for this purpose in the model.)	Contaminant coefficient for specific land uses.	Build-up tabulated by land use and surface roughness. Wash off calculated using tabulated buildup.	Can be defined for storm flow and base flow by land use as mean or stochastically generated. Default values adapted from literature.	Define build-up "method" (linear or exponential), "rate", "max", and "detachment rate" and wash-off "exponent".	Choose build-up model (linear or exponential). Define pollutant-specific properties (i.e., build-up rate constant and its saturation limit)	Since the model does not look at a full catchment, contaminant build-up and wash-off are not calculated for a catchment. They are calculated for a soil column (i.e., Bioretention water quality performance.)
LID contaminant removal	Reduction of runoff contaminant load = reduction in runoff flow volume.	Reduction of runoff contaminant load = reduction in runoff flow volume.	Tabulated removal rates based on biofilter soil and pore size.	Tabulated removal rates for TSS, TN and TP based on vegetation, exfiltration, presence of submerged zone and/or underdrain. Can add other contaminants using "swap a pollutant" feature.	Use MIKE URBAN coupled with ECO lab (equation solver) to enter user- defined equations representing water quality treatment processes.	Colloid mass balance for particle transport.	LID is not built-in. You can however model specific solute transport and removal. Particle transport uses filtration theory (e.g., modified advection-dispersion equation commonly used for colloids, bacteria, and nanoparticles).
Relevant limitations	Contaminant removal by LID is over-simplified. Contaminants are removed through different mechanisms (e.g., interception, sedimentation, diffusion for TSS) that are not equal to volume reduction. *EPASWMM	Contaminant removal by LID is over-simplified like PCSWMM.	LID contaminant removal rates are empirical based on field data from US and are limited to specific studied contaminants. Contaminant removal may vary for locations outside of US due to local factors. For unstudied contaminants, you can "swap a pollutant" but you need to know	Water quality removal rates are based on results from a single lab study in Australia for three contaminants (TSS, TN, TP). Lack of field data to support removal efficiencies. Removal rates will differ between the field and the lab due to local conditions.	Similar to EPA-SWMM add-in tool: the user needs to know the applicable treatment relationship for every contaminant of interest	Particle modelling based on colloidal-sized particles, which is not reflective of all microplastics.	Does not model catchment or directly LID. Particle modelling based on colloidal-sized particles, which is not reflective of all microplastics.

			removal rate relationship.				
Source	(Rossman, 2015)	(Liu et al., 2015b)	(PV & Associates, 2013)	(Imteaz et al., 2013b)	(DHI, 2020, 2017)	(Massoudieh et al., 2017)(Massoudieh and Aflaki, 2017)	(Šimůnek et al., 2013)

TN: total nitrogen, TP: Total phosphorus, TSS: total suspended solids

*EPA SWMM: You can build in LID water treatment with add-in tool, but the user needs to know the applicable treatment relationship for every contaminant of interest. (Tiveron et al., 2018) used a "single collector model" which has limitations (e.g., It does not account for captured particles acting as additional collectors.)

WinSLAMM

WinSLAMM splits up the particle size distribution of Total suspended solids (TSS) into seven different size classifications from 1 µm up to > 1000 µm. For each size classification, there is a different tabulated value of the mean TSS effluent concentration. To determine the total effluent concentration for TSS from a biofilter, WinSLAMM evaluates the percentage of particles in each size classification and their associated mean effluent. For example, for a specific TSS particle size distribution, 22% of TSS particles fall within the range of 10 – 30 microns. If the biofilter is made of sand and loam soil media, then 22% of the biofilter influent would have an effluent concentration of 1.55 mg/L (PV & Associates, 2023).

HSPF-BMP

HSPF-BMP, a module within the HSPF software can be used to evaluate the water quality performance of best management practice (BMPs), i.e., low impact development systems. Similarly to MUSIC and WinSLAMM, HSPF-BMP “modellers can use recommended removal fractions [based on certain studies] pertaining to assumed BMPs” (Xie et al., 2015). The user manual lists a variety of formulas for various pollutants (Johanson et al., 1980). For example, to simulate sinking of suspended material, $SNKOUT = CONC * (KSET / AVDEPE)$ where SNKOUT: fraction of material which settles out, CONC: concentration of material before deposition, KSET = sinking rate in ft/interval, and AVDEPE: average depth of water (feet) (Johanson et al., 1980). Only one study was identified that used HSPF-BMP to model total suspended solids and copper removal using low impact development systems for stormwater, specifically a dry swale and a bioretention basin (Ackerman and Stein, 2008b). For both pollutants and BMP types, pollutant removal processes were simulated with the first-order degradation process and total pollutants were evaluated as opposed to separately evaluating dissolved and particulate forms (Ackerman and Stein, 2008b). As the manual was published in 1980, it does not include a section on modelling microplastics removal using best management practices.

Example of MIKE Urban for water quality modelling of a Low Impact Development System (Hellberg, 2016)

The software includes predefined scripts in ECO Lab stating processes that occur in aquatic systems, though they are not specific to LID systems (Hellberg, 2016). An ECO Lab script can be added to any node in a stormwater catchment model, and therefore can be added to any created LID system (DHI, 2020).

Hellburg (2016) used MIKE Urban to model bioretention removal of phosphorus and metals by connecting runoff to soakaway nodes, which with couple with the software’s “ECOLab” scripts. The ECO Lab script was modified as follows to model the treatment of incoming stormwater for these two heavy metals.

$$Heavy\ metal\ removal = sorption - filtration - sedimentation$$

$$sorption = -K_d \cdot k_w \cdot [TSS] \cdot [Me^{n+}]$$

K_d = Relation between heavy metal in suspended matter and concentrations in water phase

k_w = desorption rate in water [d-1]

[Me^{n+}] = dissolved heavy metal concentration [mg/l]

[TSS] = suspended solids concentration [mg/l]

HYDRUS

Table S2. Contaminant-specific characteristics input values for colloidal pollutants.

Parameter	Description	Unit
iPsi 1 & iPsi2	Type of blocking on first and second sorption sites (0: no blocking, 1: Langmuirian, 3: random sequential adsorption, 4: depth dependent blocking coefficient)	N/A
S_{max1}	Parameter in blocking function for the first sorption sites.	N/A
S_{max2}	Parameter in blocking function for the second sorption sites.	N/A
k_{ac1}	First-order attachment coefficient for the first sorption sites.	Time ⁻¹
k_{ac2}	First-order attachment coefficient for the second sorption sites.	Time ⁻¹

k_{dc1}	First-order detachment coefficient for the first sorption sites.	Time ⁻¹
k_{dc2}	First-order detachment coefficient for the second sorption sites.	Time ⁻¹

*Note: This is an abridged version of Table 5 from (Šimůnek et al., 2015b)

Example of HYDRUS microplastic parameter values from W. Li et al. (2024):

In this study, the transport of polyethylene spheres in the range of 27 – 35 μm and of three different densities were tested in gravel and glass bed column studies. Simulations used a two-site kinetic model with depth-dependent blocking.

Table S3. Example microplastic HYDRUS parameters

PE density (g/cm ³)	K_{ac1} (min ⁻¹)	K_{ac2} (min ⁻¹)	K_{dc2} (min ⁻¹)
0.995	9.55E- 02	5.89E- 02	8.39E- 02
1	5.07E-02	3.96E-02	5.50E-02
1.12	2.47E-01	5.43E-01	3.33E-01

Section S2

Table S4. Studies on the transport of microplastics in porous media.

#	Publication	Study type	Transport Mechanisms	Size of injected Microplastics (MPs)	Use word colloid?
1	(O’Kelly et al., 2021)	Review	Most studies explain MP transport mechanisms with DLVO.	Summarized soil studies. Range: nanoparticles to 5 mm.	Yes. Refers to all MPs as colloids.
2	(Xu et al., 2023)	Review	Theoretical: Colloid filtration theory (CFT) & DLVO theory. Empirical: Advection-dispersion theory.	Summarized NMPs: Nano- and micro-plastics from 1 nm – 5 mm.	Yes, distinguishes between NMPs and colloids.
3	(F. Li et al., 2024b)	Review	Not explicitly discussed. Instead lists factors impact transport of NPs/MPs.	Summarized NPs (< 1000 nm) and MPs (1000 nm – 5 mm).	Yes, but without discussion around colloidal relevance to MP transport.
4	(Zeng et al., 2024)	Review	Fluid dynamics, KTGF and surface interaction theory (DLVO), porous media models, Darcy’s Law and Brownian diffusion.	Summarized MPs (< 5 mm).	Yes, in reference to DLVO theory and other studies of “colloidal microplastics” without a definition of this term.
5	(Geng et al., 2024)	Review	Mentions some mechanism names, but they are not discussed further.	Summarized MPs (< 5 mm).	Yes, but without explicit reference to microplastics. Not defined.
6	(Y. Xu et al., 2024b)	Review	Summarized section on the impacts of UV weathering on MP and NP transport in porous media.	Summarized NPs & MPs (< 1 µm & 1 µm - 5 mm).	Yes, in reference to natural colloids and both NPs and MPs.
7	(Hou et al., 2020)	Sand column	DLVO.	40 - 48 µm PE, unidentified morphology.	No, not to describe MPs. However, they use DLVO theory for non-colloid sized MPs.
8	(Jiang et al., 2021)	Sand column	XDLVO, Advection-dispersion-equation (ADE).	3 - 6 µm PE and PP fragments.	Yes, for colloidal sized MPs studied.
9	(Lu et al., 2021)	Sand column	DLVO.	0.05 µm PS spheres.	Yes, for colloidal sized MPs studied.

10	(Dong et al., 2021)	Sand column	DLVO, numerical model using 2 nd order kinetic deposition site.	1.08 - 2.46 μm PET fragments.	Yes, for colloidal sized MPs studied.
11	(Li et al., 2021)	Sand column	DLVO.	1 μm PS latex spheres.	Yes, for colloidal sized MPs studied.
12	(He et al., 2018)	Sand column	DLVO.	0.02, 0.2, and 2 μm PS latex spheres.	Yes, for colloidal sized MPs studied.
13	(He et al., 2020)	Sand column	DLVO.	0.02, 0.2, and 2 μm PS latex spheres.	Yes, for colloidal sized MPs studied.
14	(He et al., 2021)	Sand column	DLVO.	1 μm PS latex spheres.	Yes, for colloidal sized MPs studied.
15	(Rong et al., 2021)	Sand column	DLVO.	0.2 μm latex spheres.	Yes, for colloidal sized MPs studied.
16	(Sembiring et al., 2021)	Sand column	General filtration theories (e.g., sedimentation, Brownian motion, straining, etc.)	10 μm to >500 μm fragments and films, unidentified polymer types.	Yes, in reference to TSS.
17	(Yao et al., 2022)	Sand column	DLVO.	0.05 and 2 μm PS spheres.	Yes, refers to all MPs/NPs as colloids.
18	(Ranjan et al., 2023)	Sand column	Repulsive electrostatic double layer, mechanisms of straining, trapping, and interlocking.	< 550 μm PP, PE, and PET fragments.	No
19	(Xiaoxia Wang et al., 2022c)	Sand column	Colloid filtration theory, Two-site kinetic retention model, and DLVO.	1 μm PS spheres.	Yes, with an explicit definition of MPs as colloids

20	(Yuhao Wang et al., 2022)	Sand column	Colloid filtration theory and DLVO.	50 nm, 100 nm, 500 nm PS spheres.	Yes, with an explicit definition of MPs as colloids
21	(Fei et al., 2022)	Sand column	DLVO; Advection-dispersion-equation (ADE).	30 μm PLA and PVC, unidentified morphology.	Yes, in reference to other non-MP colloids.
22	(Qi et al., 2022)	Sand column	DLVO.	10 or 20 μm PS spheres.	No, not to describe MPs. However, they use DLVO theory for non-colloid sized MPs.
23	(Hou et al., 2022)	Sand column	XDLVO.	50 nm, 300 nm, 1 μm PS spheres.	Yes, for colloidal sized MPs studied.
24	(Xu et al., 2022)	Sand column	DLVO, One-site and Two kinetic sites models.	2 μm PS spheres.	Yes, for colloidal sized MPs studied.
25	(Sun et al., 2022)	Sand column	XDLVO, Advection-dispersion equation (ADE)	1.6 – 2.2 μm PE fragments.	Yes, for colloidal sized MPs studied.
26	(Jiang et al., 2022)	Sand column	DVLO & XDLVO, Advection-dispersion equation (ADE).	1.4 – 2.9 μm PE, PP, PS, PFTE, and PMMA powder.	Yes, for colloidal sized MPs studied.
27	(Cai et al., 2019)	Sand column	DLVO.	0.2, 1, and 2 μm PS latex spheres.	Yes, for colloidal sized MPs studied.
28	(Li et al., 2020)	Sand column	Not quantitatively evaluated. Discusses competition deposition sites and size of hetero-aggregates as mechanisms influencing MP transport.	1 μm PS latex spheres.	Yes, for colloidal sized MPs studied.
29	(Rong et al., 2023)	Sand column	DLVO.	1 μm PS latex spheres.	Yes, refers to all MPs as colloids.

30	(Chang et al., 2023)	Sand column	XDLVO.	1 μm PS spheres.	Yes, refers to natural colloids. Also MPs studied are colloid sized and they apply XDLVO theory.
31	(Vera S Koutnik et al., 2022a)	Sand column	Exponential model for vertical MP transport based on straining as a dominant removal mechanism for larger MPs.	98% > 10 μm and 75% > 100 μm PP fragments and fibers.	Yes, in reference to natural/soil colloids.
32	(Vera S. Koutnik et al., 2022)	Sand column	Exponential model for vertical MP transport based on straining as a dominant removal mechanism for larger MPs.	54% of PS sized 100 – 250 μm . Similar % of PET and PP sized 50 – 100 μm . PP, PS, and PET fragments and fibers.	Yes, in reference to natural/soil colloids.
33	(Rillig et al., 2017)	Sand column	Exact mechanisms unknown. Suggest various earthworm related transport (i.e., attachment, burrows, excrement, etc.)	710 – 2800 μm PE spheres.	No
34	(Dong et al., 2018)	Sand column	DLVO and XDLVO, convective-dispersive equation (CDE) with one-site kinetic retention.	0.1 – 2 μm PS spheres.	Yes, for colloidal sized MPs studied.
35	(Xiao et al., 2024)	Sand column	DLVO, advection-dispersion-equation (ADE).	2 μm PS spheres.	Yes, for colloidal sized MPs studied. With partial definition of colloids.
36	(Yang Wang et al., 2022)	Sand column	Colloid filtration theory, DLVO, and force analysis. Particle re-entrainment.	0.4, 2 & 10 μm PS spheres	Yes, in reference to other particles (natural organic matter, nanoparticles, and bacteria)
37	(Wang et al., 2024)	Sand column	Qualitative description of cake clogging surface layer, bridging and preferential flow.	100, 300 & 500 μm PS spheres	No.
38	(Hou et al., 2024)	Sand column	DLVO and XDLVO theories. Blocking and ripening phenomena observed with breakthrough curves.	1 μm PS spheres.	Yes, in reference to natural colloids and colloidal sized microplastics studied.

39	(Ai et al., 2024)	Sand column	Advection-dispersion equation (ADE) was used to fit the experimental breakthrough curves.	6.5 μm PP, PS, PE, PMMA, and PTFE fragments.	Yes, in reference to natural colloids.
40	(S. Zhou et al., 2024)	Sand column	Experimental breakthrough curve data simulated with advection-diffusion equation.	6.5 μm PE and PP fragments	Yes, in reference to colloidal-sized microplastics studied.
41	(Guo et al., 2024)	Sand and sandy soil mix column	DLVO theory. Experimental breakthrough curves (not simulated).	0.2 & 1 μm PS spheres	Yes, in reference to natural colloids and for colloidal transport theories applied to MPs.
42	(Gao et al., 2024)	Sand column	DLVO theory. Two-site kinetic retention model.	1 μm PS fragments	Yes, terms MPs an emerging colloidal pollutant where “MPs may have similar retention/migration properties in soil as colloids.”
43	(D. Zhou et al., 2024)	Sand column (with and without graphene oxide coating)	DLVO theory. Experimental breakthrough curves (not simulated).	1 μm PS spheres	Yes, uses colloidal transport theories for colloidal-sized MPs studied.
44	(Li et al., 2022)	Glass bead and sand columns	XDLVO. Blocking at collector convex sites and blocking & ripening at concave sites.	1 μm PS spheres.	Yes, in reference to colloidal-sized MPs studied.
45	(Zhao et al., 2021)	Glass bead column	DLVO.	1 μm PS microspheres.	Yes, with an explicit definition of MPs as colloids.
46	(Chu et al., 2019)	Glass bead column	DLVO, convection-dispersion equation.	1 μm PS latex spheres.	Yes, for colloidal sized MPs studied.
47	(Feng et al., 2022)	Glass bead column	1. Straining. 2. Physical and chemical interaction forces between MPs & substrate.	4-6 μm PE, 125 μm PE, and 5-6 μm PTFE fragments.	No, although some MPs studied are colloidal sized.

48	(Zhao et al., 2023)	Glass bead column	DLVO, Non-equilibrium Two-kinetic sites model using a 1D convection-dispersion equation.	1 μm PS spheres.	Yes, for colloidal sized MPs studied.
49	(Keller et al., 2020)	Glass bead column	Not evaluated	Nanoparticles: 187 ± 22 nm spheres, polyacrylonitrile mixed with palladium metal coated with PS. Microfibers: 30 μm thick and 510 ± 12 μm long, PET with indium oxide.	Yes, in reference to nanoplastics.
50	(Lüscher and Jo, 2022)	Glass bead and sand column	Not evaluated.	500 – 1000 μm long with 20 - 25 μm diameter PE fishing line fibers.	No
51	(Zhao et al., 2022)	Glass bead column	Deposition rate, attachment efficiency, and DLVO interaction energy	1 and 0.2 μm PS spheres.	Yes, with an explicit definition of MPs as colloids.
52	(Feng et al., 2024)	Glass bead column	DLVO theory. Two-site kinetic model	4 – 6 μm and 20 – 25 μm PE (fragments), 6 μm PMMA (spheres)	Yes, in reference to natural colloids and colloidal sized and near-colloidal sized microplastics studied.
53	(Li et al., 2024)	Gravel and glass bead columns	Observed breakthrough curves used with two-site kinetic model (with depth-dependant blocking function) to estimate MP transport parameters.	27 – 35 μm PE spheres.	Yes, indirectly as colloid theories are applied to MPs studied.
54	(Kuoppamäki et al., 2021)	Biofilter columns	Not evaluated (visual only).	10 μm PE spheres.	No
55	(Wang et al., 2020)	Biochar and sand columns	3 morphologically-controlled mechanisms: Stuck, trapped, and entangled.	10 μm PS spheres.	Yes, in reference to biochar.
56	(Xiaoxia Wang et al., 2022b)	Modified biochar and sand mixed columns	Two-site kinetic retention model/DLVO	1 μm PS spheres.	Yes, with an explicit definition of MPs as colloids

57	(Xiaoxia Wang et al., 2022a)	Modified biochar and sand mixed columns	Two-site kinetic retention model	1 μm PS spheres.	Yes, with an explicit definition of MPs as colloids
58	(Subair et al., 2024b)	Biochar column	Dominated by adsorption and filtration processes; complemented by self-agglomeration of PS particles.	< 75 μm , 75 – 150 μm , and 150 - 300 μm size ranges of PS fragments.	No
59	(Li et al., 2024)	Soil + biochar column	Influence of biochar on cracking and preferential flow paths.	1 PS spheres.	No.
60	(Okutan et al., 2022)	Silica balls, sand, and coarse gravel columns	Breakthrough curves analyzed with advection-dispersion theory.	200 – 500 μm PE fragments	Once, in reference to natural organic matter.
61	(Liu et al., 2023)	Porous pavement	Total interaction forces and Lewis acid/base force	NA	No
62	(Zhao et al., 2020)	Pore-scale column	DLVO	4.5 μm diameter PS spheres.	Yes, in reference to colloidal sized MPs studied.
63	(He et al., 2023)	Pore-scale	Describes impact of various factors on MP transport and retention but no formulas defined.	16 μm and 35 μm PE spheres.	No
64	(Dong et al., 2022)	Pore-scale	MPs transported on sand via rolling and saltating.	1.5 μm PET fragments.	Yes, in reference to sand colloids.
65	(Pradel et al., 2024)	Pore-scale	Ripening ¹ under various conditions.	0.01 - 5 μm irregular shaped PS fragments	Yes, in reference to colloidal microplastics.
66	(H. Xu et al., 2024)	Pore-scale	Two types of clogging mechanisms: independent (predominant) and dependant. No models.	Mainly between 282 – 662 μm PS fragments (d_{50} = 432 μm)	No

67	(Guo and Fei, 2023)	Numerical	Dual-site model considering both time and depth dependent deposition effects showed best performance.	NA	Yes, colloid theories applied to both MPs and natural colloids.
68	(Ryu et al., 2021)	Numerical	Attachment-detachment model for colloids	NA	Yes, with a partial definition of MPs vs colloids.
69	(Engdahl, 2018)	Numerical model (pore scale)	Transport simulated as a random walk.	1.32 - 3.32 mm long fibers. Fibers treated as bead-rod chains, no polymer type.	Yes. Refers to all MPs as larger colloids.
70	(Johnson, 2020)	Numerical model (pore scale) & Sand column	Mechanistic pore-scale and continuum scale simulations.	0.06 - 7.7 μm PS spheres.	Yes. Refers to all MPs as colloids.
71	(Lim et al., 2023)	Numerical	Advection-dispersion equation in combination with colloid filtration theory. Mechanisms include attachment, detachment, and straining.	0.1, 1, 10 μm PS spheres.	Yes, in reference to colloidal sized MPs studied.
72	(Dong et al., 2024)	Numerical	FDVLO. Under unfavorable deposition conditions, straining was the main mechanism for MP retention.	3 μm PVC, PMMA, PET, and PP fragments.	Yes, in reference to nanoplastics and inorganic colloids.
73	(Vera S Koutnik et al., 2022b)	Field study and numerical	Exponential model for vertical MP transport based on straining as a dominant removal mechanism for larger MPs.	10 μm – 2.25 mm, unidentified morphologies, and polymer types. (Note: field study, i.e. not injected MPs).	Yes, with a partial distinction between colloids and MPs.
74	(Mancini et al., 2023)	Numerical study (regression) and column study.	Straining predominant for specified MP/porous media size ratio. Exponential regression per polymer type/shape category.	0.57 - 4.43 mm PET spheres, PET pellets, PS fragments, and PA fishing line fibers of 0.18 mm, 0.26 mm, and 0.35 mm in dia.	No
75	(O'Connor et al., 2019)	Sand column (regression)	MP depth prediction based on PE penetration and wet-dry cycles	Average diameter: 21 - 535 μm PE and PP spheres with granular shapes.	Yes, but not in reference to MPs in this study. Distinguishes

					between MPs and colloids.
76	(Gao et al., 2021)	Sand column (regression)	Exponential regression of MP penetration depth vs. concentrations	10 - 450 µm PE, PET, PP, and PA fragments.	Yes, but not in reference to MPs in this study. Distinguishes between MPs and colloids.
77	(Waldschläger and Schüttrumpf, 2020b)	Glass bead column (regression)	Exponential regression based on MP morphology	0.6 - 5 mm PE, PP, PS, PA, PET, CoPA, and SBR tire fragments, pellets, spheres, fibers.	No. Distinguishes between MPs and colloids.

Acronyms: PE: polyethylene, PP: polypropylene, PS: polystyrene, PA: polyamide, PET: polyethylene terephthalate, PVC: polyvinyl chloride, PLA: polylactic acid, PTFE: Polytetrafluoroethylene, PMMA: Poly(methyl methacrylate), CoPA: copolymer of nylon 6 and nylon 6,6, and SBR: styrene butadiene rubber. NMP: Nano- and micro-plastics. KTGF: Kinetic theory of granular flow. DLVO: Derjaguin–Landau–Verwey–Overbeek theory is used to quantify “double layer electrostatic forces and van der Waals interactions between particles” (O’Kelly et al., 2021). XDLVO: Extended-DLVO theory is “the sum of van der Waals attraction, electric double layer repulsion, osmotic, elastic, and hydrophobic force (Jiang et al., 2021). Ripening: Inside packed beds, “growth of small deposits in the most confined parts, by wedging or straining, and also on the open surfaces, on which there is colloidal aggregation.”¹

Confusion when interpreting microplastics as colloids

Some reviewed articles ($n = 6$) incorrectly refer to all microplastics as being colloids. Other articles evaluate the transport of slightly larger non-colloidal sized microplastics; however they use colloidal transport theories (Hou et al., 2020; Li et al., 2024; Qi et al., 2022). For example, (Hou et al., 2020) evaluates 40 – 48 μm sized microplastics. However, it uses Derjaguin, Landau, Verway and Overbeek (DLVO) theory to explain microplastic transport behaviours (Hou et al., 2020). This is of interest as DLVO theory describes colloidal stability interactions between colloids or surfaces and colloids in terms of van der Waals and electrostatic double layer forces (Baalousha et al., 2009). This article therefore indirectly refers to microplastics as colloids and uses a colloidal theory for non-colloidal particles. This is of interest because the extent to which microplastics behave like colloids remains unknown (Gao et al., 2021; Guo and Fei, 2023; O'Connor et al., 2019).

Most of the transport studies included in this review (36 articles or 49%), correctly use the term colloid whether in reference to microplastics or non-microplastic colloids studied such as clay and biochar particles. These studies do not create confusion around the term colloids in reference to microplastics, however, they point out the need for more porous media transport studies of larger non-colloidal sized microplastics.

Finally, some studies partially ($n = 7$; 9%) or explicitly ($n = 6$; 8%) define colloidal microplastics. For example, Xiao et al., (2024) defines large colloids $> 1 \mu\text{m}$. Vera S Koutnik et al., (2022a) distinguishes between this study's microplastics and soil colloids and Vera S Koutnik et al., (2022b) describes filtration mechanisms for differently sized MPs (i.e., $> 5 \mu\text{m}$ vs $> 10 \mu\text{m}$ sized MPs). Sembiring (2021) defines colloids in reference to total suspended solids and Ryu et al.,(2021) defines microplastics versus colloids, but without an explicit numerical definition. Whereas, some other studies give an explicit definition where “microplastics in the particle size range of 1 – 1000 nm have been reported to exhibit colloidal properties” (Xiaoxia Wang et al., 2022c, 2022b, 2022a; Yuhao Wang et al., 2022). Likewise, Zhao et al. (2021) specifically define “particles with colloidal properties ranging in size from 1 nm to tens of microns” and describes some properties of these microplastics as those which easily migrate and adsorb strongly. These explicit definitions help clarify which range of microplastics the authors consider to be colloids and therefore justifies relevant colloidal theories which they apply to them.

Table S5. Bioretention studies evaluating microplastics fates within their soil media.

Study	Type of LID	# Bio. Cells	Sample processing	Sample locations	Size range of MPs	Plastic ID?	Analytical technique	Type of sample	Concentration range (n= # samples)
(Mbachu et al., 2022)	Bioretention cells (BCs)	Field: 20 BCs in Australia (various ages from 3 - 14 years).	H ₂ O ₂ 30%, enzyme, ZnCl ₂ density separation.	Inlet, Middle, Outlet: 400 mm depth from 250 mm ² area. Total 100 g soil (collected with hand auger.)	Micro (72 μm – 5 mm) and Mesoplastics (5 - 25 mm).	Yes. Mesoplastics: PS>PP>nylon ; fragments dominant. Microplastics: PE>PP and fragments dominants. Fibers not found despite intended inclusion.	Visual observation + ATR-FTIR.	Horizontal distribution in soil samples.	Average: 41 ± 30.5 mesoplastics/kg; 55 ± 342.8 microplastics /kg
(Mengistu et al., 2022)	Bioretention cell	Field: One BC in Norway. Plus, a column study using road runoff as influent.	Homogenize soil with blender. 30 g soil sub-sample. Size-fractionated.	Topsoil (0 – 5 cm) with soil-sampling tube: 3 spots at inlet and 3 spots 5 m horizontally into BC. For column: top 5 cm and bottom 5 cm.	Tire wear particles (TWP from <50 μm to >500 μm). **STA-FTIR detection limit: 1.1 mg/g for TWP.	Yes	Simultaneous thermal analysis coupled with FTIR (STA-FTIR).	Soil samples in BC and column lab study.	Inlet: 30.9 ± 4.1 mg/g, 5 m from inlet into BC: 19.8 ± 2.4 mg/g. Column study: 5 ± 1.4 mg/g in top 5 cm soil, <MDL in bottom 5 cm soil.
(Lange et al., 2022a)	Bioretention cells	Field: 9 BCs in Ohio and Michigan, USA (7-12 years old)	Fenton's, ZnCl ₂ density, some had cellulose dissolution step	Two at 0 - 5 cm depth for all sites. Location 1 had one sample at 10 - 15 cm depth +	40 μm – 5 mm	Yes. Most abundant were PP, EVA, PS, and EPDM rubber. Up to 59% black	Done by commercial lab (ALS Scandinavia). μFTIR using siMPle and ATR-FTIR.	Soil samples from field sites.	448 MP particles/100 g soil at 0 - 5 cm soil depth to 136 MPs/100 g

				some at forebays. Collected with steel spade into PA plastic bags.		coloured MPs by sample.	Note no field blanks, only lab blanks.		soil at 10 - 15 cm soil depth.
(Vera S Koutnik et al., 2022b)	Mainly swales and bioretention cells	Field: 14 SCMs in Los Angeles (Appear visually to all be bioretention cells or bioswales.)	1 g of soil, KI solution density separation with centrifuge, filtered onto cellulose filter, Nile Red dye used.	Above canopy and below ground in subsurface on May 20 - 21, 2021. (0 - 2 cm depth and 8 - 10 cm depth at 3 random spots in and outside SCM 2 - 15 m away). Collected with steel hand auger (2.5 cm diameter). Leaves also collected to measure canopy MPs (washed, sonicated, Nile red dye.)	10 µm – 2.25 mm.	Particles dyed with Nile red and counted with image processing using smartphone. Shapes of particles not analyzed. Polymer types not identified due to methods.	No field blanks, only lab blanks.	Depth-wise soil samples + plant leaf samples for canopy MPs.	Varied from 0 and 2784 particles/g soil based on location + depth of soil. MP concentration decreased exponentially with soil depth. Concentration of MPs on leaves increased with height up to 1.5 m above ground then decreased at higher altitudes > 1.5 m.
(Beaurepaire, 2024)	Biofiltration swale (BFS)	Field: One BFS 20km from Paris, France.	5 g soil samples, H ₂ O ₂ 30%, NaI density separation	9 cores spaced out by 20 cm. Sample core depths of 0 – 5 cm, 5 – 15 cm, 15 – 25 cm, and 25 – 35 cm	25 µm – 5 mm	Yes, the three most abundant polymers were PP, PE, and PS. Pyro-GC-MS also found styrene-butadiene-rubber (SBR)	µFTIR imaging + Pyro-GC-MS	Soil samples from field site.	Median microplastic values at soil surface: 28.6 MP/g; at 5 - 15 cm depth: 3 MP/g; at 15 - 25 cm depth: 12 MP/g and at 25 – 35 cm

						and butadiene rubber (BR).			depth: 2.4 MP/g. Mean SBR+BR at soil surface: 2.19 mg/g and in deeper soil: 0.11 mg/g.
(Vera S Koutnik et al., 2022a)	Simulated biofilter: Made of soil collected from Los Angeles roadside and/or sand mixtures.	Column study: 8 columns, each filled with 15 cm of media with underlying drainage layer of glass wool and pea gravel. Simulated stormwater (NaCl in DI water). Four columns each with a duplicate subjected to either drying or freeze-thaw cycles.	None for column effluent water: vacuum filtered onto glass fiber filters (1.2 µm pore) and dosed with Nile Red dye. For column soil: same as (Vera S Koutnik et al., 2022b) (KI, Nile red, etc.)	Column soil depth increments from 0 – 12.5 cm.	PP fragments and supposedly fibers made from sanding PP. Size distribution analyzed with laser particle size analysis: approx. 75% MPs >100 microns and >98% MPs >10 µm.	No. Same as (Vera S Koutnik et al., 2022b)	NA: Used Nile red and visual identification.	Vertical distribution.	Exponential model found for MPs with soil depth (same as (Vera S Koutnik et al., 2022b)). Freeze-thaw cycles appear > dry-wet cycles at moving MPs downward. Mobility of MPs more in sand columns than in soil, but more collector particle colloids released from soil column.
(Kuoppamäki et al., 2021)	Simulated biofilters: Five different types by media	Column study: Five different media types. Planted with reed grass or none.	None	Column media depths	Spiked with fluorescent PE MP beads (up to 10 µm in diameter).	No. Visually identified spiked fluorescence beads.	Visual identification	Vertical distribution	MP beads primarily around plant roots. Max infiltration depth 8 - 12 cm in

		Stormwater collected as snow next to road.							vegetated system vs. 4 - 6 cm in non-vegetated. No MP quantities measured, only TSS.
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Acronyms: TWP: Tire-wear particles; MDL: method detection limit; KI: potassium iodide, DI: deionized, PP: polypropylene; PE: polyethylene

Analytical technique differences for bioretention studies in Table S5

Mbachu et al. (2022) used techniques of visual identification and ATR-FTIR for polymer identification. Black rubber particles were not identified likely due to method limitations and though they were not purposefully excluded from the methods, they did not identify any fibers. Mengistu et al. (2022) used a novel analysis method of STA-FTIR to identify tire wear particles only and results were therefore reported in mass and not particle quantities. Lange et al. (2022a) used both μ FTIR mapping with siMPle for direct quantification and polymer identification as well as ATR-FTIR for individual particle analysis to identify common microplastics and they were also able to identify black EPDM rubber with this method. Vera S Koutnik et al. (2022b) used Nile red dye to stain suspected microplastics and directly quantified dyed microparticles without other polymer identification methods. This makes it unreliable to compare with other studies as Nile Red dye is known to stick to both microplastics and organic matter if it's not completely removed prior to staining. This results in overestimation of microplastic counts.

Table S6. Bioretention black-box studies: microplastic stormwater removal rates

Study	Study type	Location	Bioretention design	Removal efficiency	Microplastics studied	Analysis method
(Gilbreath et al., 2019b)	Field	1 cell roadside, El Cerrito, California	Vegetated, 46 cm depth media (70% sandy loam, 10% clay, and 20% organic matter), underdrain, exfiltration allowed	83 – 95 % particle concentration decrease (n = 3 storms)	> 125 µm	Visual microscopy, Raman spectroscopy (subset)
(Werbowski et al., 2021b)				91 % – 98 % particle concentration decreased (n = 3 storms)		Visual microscopy, Raman Spectroscopy, Pyro-GC-MS for 9 rubbers
(Smyth et al., 2021b)	Field	1 cell parking lot adjacent, Greater Toronto, Canada	Vegetated, hardwood mulch, 40 cm depth media (93-99% sand and 1 – 7 % silt and clay)(Rhodes-Dicker and Passeport, 2019), underdrain, exfiltration allowed	84 % median microparticle concentration reduction (12 storms)	106 µm – 5 mm	Visual microscopy, Raman spectroscopy (subset)
(Smyth et al., 2024)				71 % median microplastic concentration reduction (n = 11)		µFTIR spectroscopy automated mapping

				storms)		
(Lange et al., 2021b)	Field	1 cell highway adjacent, Sundsvall, Sweden	Vegetated, 50 cm sand-based media (median diameter, $D_{50} = 0.77$) covered with gravel and 30 mm deep turf, underdrain	> 70% (n = 9 storms)	100 μm – 5 mm	Visual stereo microscopy
(Lange et al., 2022c)				92 ± 6 % (n = 9 storms)	20 - 100 μm	μFTIR mapping with simple, ATRFTIR for rubber
(Johansson et al., 2024)	Mesocosm	13 mesocosm columns, highway stormwater, Gothenburg, Sweden	Vegetated, layered media: First 15 cm sandy loam mixed with pumice stone; then next 65 cm: the same materials mixed with a sorption material (either Sphagnum peat, biochar, or combination of peat, biochar, metal-sorted and aged bottom ash from municipal solid waste incineration), underlaid with fine sand and gravel. Bottom 11 cm consist of an internal water storage zone.	98 - 100% for PI, PB, PVC, PS, PET, PA6, PC and PMMA. > 83% for PE and PP. (n = 16 irrigations with 20-70 L of stormwater applied per filter) (Removal rates observed after 53 days from start-up.)	> 10 μm	Pyrolysis GC-MS
(Struzak et al., 2024)	Mesocosm	9 mesocosm columns, parking lot	61 cm media layer (either 100% Portland bioretention soil mix, BSM, (i.e., 60-70% loamy sand	85 – 87 % (n = 5 trials, where each trial applied 24 L of stormwater)	56 μm to > 5mm	Visual stereo microscopy

		stormwater	and 30-40% compost), or 25% biochar and 75% BSM or 50% biochar and 50% BSM), internal water storage zone, underdrain			
(Wolfand et al., 2023)	Lab columns	9 columns, microplastic-spiked stormwater		99.8-100% (where each trial applied 13.6 L of spiked stormwater)	106 µm - 5mm spiked ABS shaved fragments dosed at approximately 176 microparticles/L.	Visual stereo microscopy, ATR-FTIR
(Mufidah and Soewondo, 2023)	Lab columns	3 columns, microplastic-spiked tap water	2 vegetated columns and 1 non-vegetated, 60 cm media (25% topsoil, 60% medium sand and 15% compost)	92.4 – 99.3 % (where 3 different simulated rainfall intensities were tested on each column)	25 µm – 5 mm spiked microplastics made from scraped vehicle tires	Visual stereo microscopy
(Vijuksungsith et al., 2024)	Lab columns and mesocosms	3 microcosms: Tap water with spiked microplastics in lab and real wastewater	1 non-vegetated microcosm, 2 vegetated microcosms. Called both bioretention systems and horizontal subsurface flow systems. Filter media consisting of different ratios of gravel: sand: soil.	Wastewater mesocosms: 95.45 % for sizes >1000 µm, 89.21 % for a size range of 500–1000 µm, and 44.16 % for sizes < 500 µm. Lab: 100% for spiked microplastics > 0.5 mm.	Not specified. Large enough for visual identification.	Visual stereo microscopy

		in mesocosms				
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Note: polyisoprene (PI), polybutadiene (PB), polyethylene (PE), polypropylene (PP), polyvinylchloride (PVC), polystyrene (PS), polyethylene terephthalate (PET), polyamide 6 (PA6), polymethylmethacrylate (PMMA), polycarbonate (PC), and acrylonitrile butadiene styrene (ABS).

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