Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 2533

Mitigating Urban Microplastic Pollution

Investigating Nature-Based Filters in Stormwater Management

GABRIELLA RULLANDER

ACTA UNIVERSITATIS
UPSALIENSIS
2025

ISSN 1651-6214
ISBN 978-91-513-2466-1
urn:nbn:se:uu:diva-554039

UPPSALA
UNIVERSITET

Dissertation presented at Uppsala University to be publicly examined in Hambergsalen, Geocentrum, Villavägen 16, Uppsala, Wednesday, 28 May 2025 at 10:00 for the degree of Doctor of Philosophy. The examination will be conducted in English. Faculty examiner: Dr Shima Ziajahromi (Griffith university, Australia).

Abstract
Rullander, G. 2025. Mitigating Urban Microplastic Pollution. Investigating Nature-Based Filters in Stormwater Management. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 2533. 63 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-513-2466-1.

Microplastic (MP) pollution has emerged as a global environmental concern, particularly in urban environments, where stormwater serves as a major transport pathway for MPs into aquatic ecosystems. This thesis investigates MP sources, distribution, and removal strategies in urban settings, with a focus on stormwater filtration solutions. Field studies were conducted in Uppsala, Sweden, to assess MP contamination in road dust and spider webs (**Paper I**). Results indicated spatial variability, with indoor parking lots exhibiting the highest MP loads, predominantly polyurethane. Spider webs effectively captured airborne MPs, and particularly polyester fibers, demonstrating their potential as passive samplers of atmospheric pollution. To mitigate MP transport via stormwater, laboratory and pilot-scale filtration experiments were conducted using sand, bark, and biochar as filter materials (**Papers II-IV**). Laboratory-scale horizontal flow filters demonstrated high MP retention across all tested materials. However, results indicated that the retention efficiency was influenced by MP shape and size, with fibers being particularly well retained. Additionally, biochar-beds suggested a polarity-dependent filtration effect, preferentially removing non-polar MPs over polar MPs, emphasizing the role of polymer properties in filtration performance (**Paper IV**). The pilot-scale biochar-beds were tested with semi-artificial stormwater and with simulated environmental stressors, including prolonged drying and road salt exposure (**Paper IV**). Results revealed that biochar efficiently removed MPs and particulate-bound metals. Environmental factors influenced filter performance; drying-induced structural changes in biochar resulted in an initial surge of MP release upon rewetting, and pH shifts altered metal speciation and reduced metal removal efficiency. This research advances the understanding of urban MP pollution and its remediation, demonstrating that filtration-based stormwater treatments can effectively capture MPs before they reach aquatic ecosystems. The findings emphasize the need for environmentally robust stormwater management solutions and highlight the importance of considering real-world stressors in filtration system design. Future studies should explore long-term filter performance and the combined effects of multiple environmental stressors to optimize MP removal strategies.

Keywords: Aquatic ecosystems, biochar, environmental stressors, filtration, horizontal flow filters, LIDs, Low Impact development, microplastics (MPs), passive samplers, pilot-scale experiments, polymer properties, road dust, sand, spider webs, stormwater, stormwater management, SUDs, urban environments, water pollution.

Gabriella Rullander, Department of Earth Sciences, LUVAL, Villav. 16, Uppsala University, SE-75236 Uppsala, Sweden.

ISSN 1651-6214
ISBN 978-91-513-2466-1
URN urn:nbn:se:uu:diva-554039 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-554039)

Till min farmor, Britt

List of Papers

This thesis is based on the following manuscripts and papers, which are referred to in the text by their Roman numerals.

I. Iordachescu, L., **Rullander, G.,** Lykkemark, J., Dalahmeh, S., & Vollertsen, J. (2024). An integrative analysis of microplastics in spider webs and road dust in an urban environment–webbed routes and asphalt trails. Journal of Environmental Management, 359, 121064. https://doi.org/10.1016/j.jenvman.2024.121064

II. **Rullander, G.,** Lorenz, C., Herbert, R. B., Strömvall, A-M., Vollertsen, J., & Dalahmeh, S. S. (2023). How effective is the retention of microplastics in horizontal flow sand filters treating stormwater? Journal of Environmental Management, 344, 118690. https://doi.org/10.1016/j.jenvman.2023.118690

III. **Rullander, G.,** Lorenz, C., Strömvall, A-M., Vollertsen, J., & Dalahmeh, S. (2024). Bark and biochar in horizontal flow filters effectively remove microplastics from stormwater. Environmental Pollution, 356, 124335. https://doi.org/10.1016/j.envpol.2024.124335

IV. **Rullander, G.,** Herbert, R. B., Strömvall, A-M., Vollersten, J., Lorenz, C., Rauch, S., Mohammadi, A. S., & Dalahmeh, S. (2025). Removal of microplastics and metals in biochar beds: Effects of prolonged drying and salinity on pollutant mobility. *Manuscript*

Contribution to the above papers

Paper	Idea development	Research study design	Data collection	Data extraction and analysis	Manuscript preparation	Submission and response to reviewers
I	Shared responsibility	Shared responsibility	Shared responsibility	Contributed	Shared responsibility	Contributed
II	Shared responsibility	Shared responsibility	Responsible	Responsible	Responsible	Responsible
III	Shared responsibility	Shared responsibility	Responsible	Responsible	Responsible	Responsible
IV	Shared responsibility	Shared responsibility	Responsible	Responsible	Responsible	Responsible

Responsible: led the development and implementation of a plan to complete the task, consulting others when necessary. **Shared Responsibility**: played a key collaborative role in completing the task alongside other research team members. **Contributed**: provided support or input that aided in completing the task, without leading or sharing primary responsibility.

Contents

Abbreviations

Biochar	A carbon-rich material derived from biomass pyrolysis
Cd	Cadmium
C_c[1]	Constant of curvature (a measure of the uniformity of particle size distribution)
Cu	Copper
C_u[2]	Coefficient of uniformity (ratio of particle sizes indicating material gradation)
DI Water	Deionized water (pure water without ions, used in experiments)
$Fe(OH)_3$	Iron hydroxide (solid phase)
$FeSO_4$	Iron (II) sulfate (used in the Fenton reaction for organic matter oxidation)
GC-MS	Gas Chromatography-Mass Spectrometry
H_2O_2	Hydrogen peroxide (used in chemical oxidation for microplastic extraction)
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
LID	Low Impact Development (sustainable stormwater management techniques)
MP	Microplastic
Mn	Manganese
Ni	Nickel
PA	Polyamide (e.g., Nylon, commonly found in textiles)
PA6.6	Polyamide-nylon 6.6 (a type of synthetic polymer used in textiles)
PAH	Polycyclic Aromatic Hydrocarbon (organic pollutants found in stormwater)
Pb	Lead
PET	Polyethylene terephthalate (e.g., used in beverage bottles and synthetic fibers)

[1] C_c is calculated as, $D_{30}^2/(D_{60}\times D_{10})$, where D_{10}, D_{30}, and D_{60} are the particle sizes in which 10, 30, or 60 percent of the particles are finer than the specified size.
[2] C_u is calculated as, D_{60}/D_{10}.

PMMA	Polymethyl methacrylate (commonly known as acrylic or Plexiglass)
PP	Polypropylene (e.g., used in packaging)
PS	Polystyrene (e.g., used in foam cups and insulation materials)
PVC	Polyvinyl chloride (e.g., used in pipes and flooring)
PU	Polyurethane (e.g., used in coatings, adhesives, and foams)
SPT	Sodium Polytungstate (high-density solution used for density separation of microplastics)
SEM	Scanning Electron Microscope
TSS	Total Suspended Solids (solid suspended particles in water affecting water quality)
TWP	Tire Wear Particle
Zn	Zinc
μFTIR	Micro-Fourier Transform Infrared Spectroscopy

Introduction

The rise in the use of plastic materials began in the 1940s, as industrialized nations sought inexpensive, synthetic alternatives to wood, glass, and metals. Quickly becoming a symbol of technological progress, plastics fueled a surge in production. In 1950, yearly plastic production was 1.5 Mt, which escalated over the decades, reaching 368 Mt in 2019 and surpassing 400 Mt by 2022 (PlasticsEurope, 2020, 2023). Today, an estimated 8 Gt of plastic exists in either active use or waste, exceeding the combined mass of all terrestrial and marine animals (Elhacham et al., 2020).

Over the decades, several different types of plastics have been produced, such as polyamide (PA), polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS) and polyvinyl chloride (PVC). These materials revolutionized industries by enabling the production of items such as single-use plastics, food containers, plastic toys, spectacle frames, and drinking bottles (Geyer et al., 2017). To enhance their properties for specific applications, chemical additives such as flame retardants, coloring agents, and plasticizers are incorporated into the polymers (Hahladakis et al., 2018). These additives contribute to the durability and longevity of plastics, allowing them to persist in the environment for centuries before fully degrading.

The durability of plastics, once seen as an advantage, has led to their widespread accumulation in the environment. By the late 20th century, plastic debris had infiltrated even the most pristine ecosystems and was observed in a broad range of sizes. Thompson et al. (2004) first defined microplastics (MPs) as plastic particles smaller than 5 mm. In the same study, they identified MPs in marine sediments and raised concerns about their potential ingestion by aquatic organisms. Since then, MPs have been further classified into two categories: primary and secondary MPs. Primary MPs are intentionally manufactured as small plastic particles for specific applications, such as microbeads in personal care products, while secondary MPs result from the degradation of larger plastic debris through natural weathering processes (Hartmann et al., 2019).

Early MP research primarily focused on marine pollution. However, growing evidence suggests that stormwater is a major transport pathway, carrying MPs from urban areas into vulnerable aquatic ecosystems (Werbowski et al., 2021), ultimately reaching the marine environments (Siegfried et al., 2017). Urbanization plays a key role in this process: as natural landscapes are replaced with impervious surfaces like roads and buildings, surface runoff increases due to reduced natural infiltration through soil and vegetation (Dhakal & Chevalier, 2016). Unlike wastewater, urban runoff often bypasses treatment systems entirely, and MP concentrations in stormwater have been shown to exceed those found in treated wastewater effluents (Jönsson, 2016; Werbowski et al., 2021). Together, these findings highlight the urgent need to prioritize mitigation strategies targeting stormwater pollution.

Aim and Objectives

This thesis aims to advance our understanding of MP pollution in urban environments and assess effective mitigation strategies. Specifically, it explores the impact of urban activities on MP pollution in road dust from parking areas in Uppsala City, Sweden, while also examining the role of airborne MPs via spiderweb sampling. Additionally, the thesis evaluates filtration-based approaches for MP removal, focusing on the effects of filter material properties and the intrinsic characteristics of MPs (e.g., size, shape, and type). To support sustainable remediation efforts, the thesis also investigates the efficiency of pilot-scale biochar beds in removing MPs and metal pollutants from stormwater, derived from urban road dust, under different environmental stress conditions. To achieve these goals, the following research questions are addressed:

1. What types and abundances of MPs can be identified in urban surfaces and surrounding air in parking lots in Uppsala, Sweden?
2. How effective is MP removal in horizontal flow filters using sand, biochar, and bark materials, considering variations in MP size, shape, and type?
3. How do environmental stressors, like dry periods and road salt, affect the efficiency of pilot-scale biochar beds in removing MPs and metal pollutants from stormwater?

The thesis is based on data generated from a field study **(Paper I)** and laboratory experiments **(Papers II and III)**, including a pilot-scale experiment **(Paper IV)**. Below is a brief overview of the main aspects of the studies, and their objectives (Figure 1).

Paper I investigates potential sources of MP pollution in urban areas, using Uppsala City as a case study. Road dust and spiderweb samples were collected from seven outdoor and one indoor parking lot. The study analyzes MP types, quantities, and mass estimates across various catchment areas (city center, commercial, industrial, recreational, and residential), spatial distributions (curb, middle, and drive-in lanes), and sample types, addressing both settled MPs (road dust) and airborne MPs (spider webs). The paper addresses research question 1.

Paper II examines the effectiveness of lab-scale sand filters (25, 50, and 100 cm lengths) in removing MPs at a constant flow rate of 1 mL/min. The study investigates the removal of MPs of differing types, sizes, and shapes, as well as their retention within the sand. This paper addresses research question 2.

Paper III examines the effectiveness of lab-scale filters (25, 50, and 100 cm lengths) of bark and biochar in removing MPs at a constant flow rate of 5 mL/min. The study investigates the removal of MPs of different types and sizes, as well as their retention within a 100 cm filter containing pine bark. This paper addresses research question 2.

Paper IV examines the removal of MPs from artificial stormwater, created using road dust collected from commercial parking lots (**Paper I**). This study extends the previous work by evaluating the simultaneous removal of MPs and common metal pollutants under induced prolonged dry periods and road salt exposure. It also investigates biochar's efficiency in removing both polar and non-polar MP types. This paper addresses research questions 2 and 3, while also contributing to aspects of research question 1.

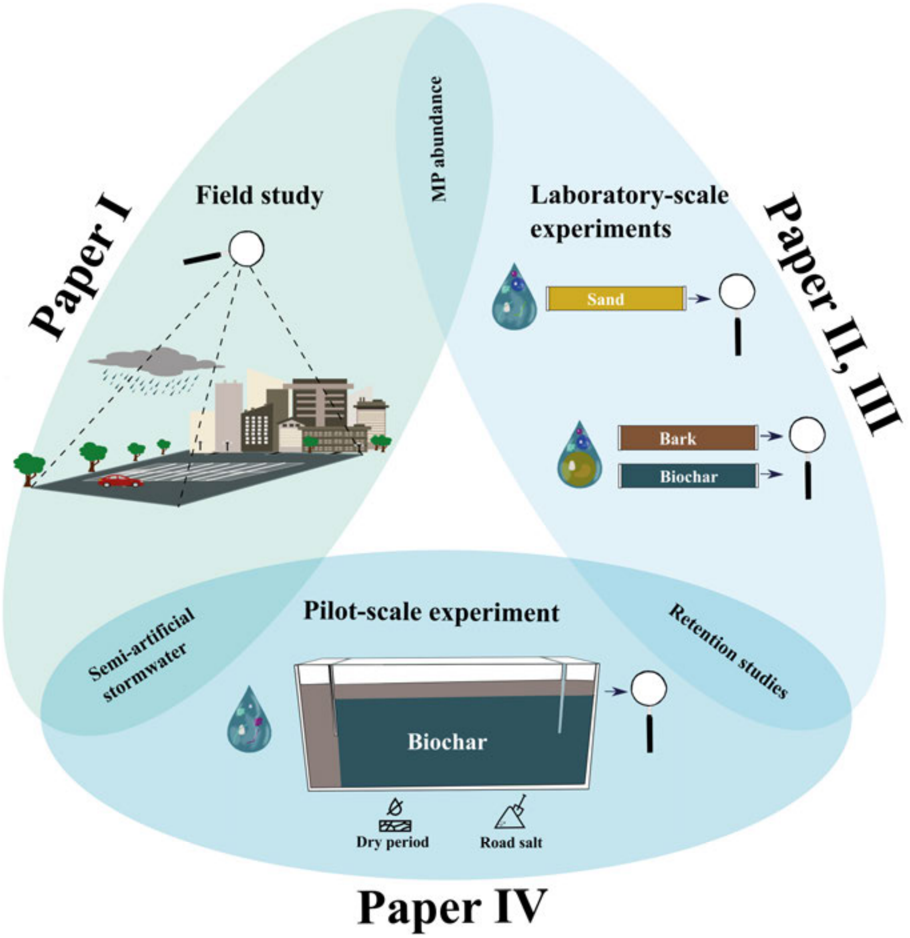

Figure 1 Illustrative overview of the thesis, showing the connections between **Papers I, II, III, and IV**.

Background

Why focus on microplastics in stormwater?

Urban stormwater forms when precipitation generates surface runoff, carrying natural particles (e.g., soil and organic matter) along with anthropogenic pollutants. The composition of stormwater reflects the heterogeneity of urban environments, often containing contaminants such as organic pollutants (e.g. polycyclic aromatic hydrocarbons, PAHs) and phthalates (Björklund et al., 2009; Markiewicz et al., 2017), as well as TSS, nutrients, toxic metals and pathogens (Müller et al., 2020). More recently, stormwater has also been identified as a significant transport pathway for MPs (Werbowski et al., 2021). Since plastic is a synthetic material designed to meet human needs, MP pollution is particularly pronounced in urban areas where human activity is most intense (Dris et al., 2015), and MP concentrations in both water and aquatic biota have been shown to rise with proximity to urban areas (Baldwin et al., 2016). Common sources of MP pollution include plastic components in infrastructure and recreational areas, construction sites, road paint, and combined sewer overflows, which often contain synthetic fibers from household laundry. Higher population density further contributes to increased litter, single-use plastic waste, and traffic-related MP emissions (Gaggini et al., 2024; Järlskog et al., 2020; Liu et al., 2019; Österlund et al., 2023).

MPs can accumulate in surface road dust in urban areas, particularly over extended dry periods (Monira et al., 2021; Vogelsang et al., 2019). Their subsequent transport via stormwater is influenced by hydraulic dynamics (e.g. rain intensity and duration), their interactions with other stormwater components, and the intrinsic physical and chemical characteristics of the MPs themselves. For instance, rain events often trigger a "first flush" effect, in which a high concentration of MPs is rapidly mobilized during the early stages of runoff (Do et al., 2023; Sun et al., 2023). This initial surge is further intensified by the deposition of airborne MPs, which are most prevalent in the initial rainfall (Szewc et al., 2021). MP transport is further complicated by their heterogeneous nature, ranging from 1 µm to 5 mm in size and varying in polymer type and shape, which significantly influences their mobility and interactions with other stormwater components (Kooi et al., 2018). Additionally, environmental processes such as weathering, biodegradation, and biofouling can alter

MP properties over time, introducing further complexity to their behavior and fate in aquatic systems (Rummel et al., 2017; Shah et al., 2008).

Studies on MP concentrations in stormwater reveal significant variability, influenced by factors such as sample type, sampling methods, location, pre-treatment and analysis techniques, and the size range of MPs reported (Shafi et al., 2024). Despite this variability, stormwater research consistently indicates an inverse relationship between MP concentration and particle size (Smyth et al., 2021). For instance, Järlskog et al. (2020) showed that 99.94% (5900 MPs/L) of MPs found in stormwater were larger than or equal to 20 µm, while only 3 MPs/L were larger than 100 µm. The most frequently identified MPs in stormwater include fragments and fibers of PP, PE, and PET, with other frequently used urban plastics, such as PS, PA, and PVC, also contributing to MP pollution (Wei et al., 2023).

A major concern with MP-polluted stormwater is its role in transporting MPs into sensitive aquatic ecosystems (Horton et al., 2017). Once introduced, MPs can be ingested by organisms and accumulate in the food web (Amelia et al., 2021), potentially causing physical harm and digestive irritation. Additionally, chemical additives may leach from MPs, and MPs themselves may act as carriers for other organic micropollutants (Arias et al., 2019; Hahladakis et al., 2018; Nelms et al., 2018; Ribeiro et al., 2019). Given these environmental risks, developing effective MP removal strategies is crucial for stormwater management.

How can we manage microplastic pollution in stormwater?

Urban environments are distinguished by impermeable surfaces, hindering the natural percolation of stormwater during rain events. Thus, stormwater management initially aimed to mitigate issues regarding runoff quantities. In some cities, stormwater is collected jointly with wastewater in combined collection systems and later processed in centralized wastewater treatment plants. However, most stormwater is distributed in separate pipe systems, and discharged without treatment. Today, upstream and onsite treatment of stormwater is increasingly implemented to enhance the stormwater quality. The goal is to decentralize the treatment and address pollutants before they reach recipient water bodies and become difficult to remove. This approach is also relevant for targeting MPs in stormwater (Vivekanand et al., 2021).

In recent years, there has been a surge to incorporate low impact developments (LIDs) into urban stormwater management strategies. LIDs are sustainable practices that aim to manage stormwater by mimicking natural hydrological processes, thereby reducing runoff and improving water quality (Fan et al., 2022). Although these systems were not originally designed to target MPs, emerging research has begun to examine their potential for MP removal. Studies have explored the effectiveness of various LIDs, such as bioretention cells (Gilbreath et al., 2019; Kuoppamäki et al., 2021; Lange et al., 2021, 2022; Smyth et al., 2021), constructed wetlands (Chen et al., 2021; Wang et al., 2020a; Ziajahromi et al., 2020) and retention ponds (Liu et al., 2019; Olesen et al., 2019). Depending on the technique at hand, the primary removal mechanisms of stormwater pollutants differ. In stormwater retention ponds and constructed wetlands, MP removal largely depends on particle sedimentation. In contrast, for decentralized filtration-based techniques, such as bioretention cells, the primary removal mechanism for MPs is filtration through porous media, with or without, vegetation. Comparing the efficiency of MP removal across different treatment techniques is challenging, due to the complexities in evaluating MP abundance in stormwater. Nevertheless, various techniques have demonstrated potential for MP removal. This thesis focuses specifically on filtration-based methods, which have achieved removal efficiencies ranging from 70–100% (Table 1). The performance of these techniques is largely influenced by the type of filter media used, presenting opportunities to explore and optimize materials to enhance MP removal. It is worth noting that bioretention cells, sometimes referred to as rain gardens, often include vegetation, which can also play a role in MP removal. However, the impact of vegetation was not incorporated into the scope of this thesis.

Table 1 Removal efficiencies of MPs identified in the literature for common decentralized stormwater filtration systems.

Treatment type	Site location	MP sizes (µm)	MP types	MP removal (%)	Source
Bioretention	Canada	106–1000	PES, PU, and PE	84	Smyth et al. (2021)
	Sweden	100–300	Rubber, bitumen, other MPs	>70	Lange et al. (2021)
	Sweden	20–100	PP, PE, PVC, PS, PA, PU, EVA, black rubber	>90	Lange et al. (2022)
	USA	125–355	Fibers, fragments, microbeads, rubber, paint particles	90	Gilbreath et al. (2019)
	Lab-scale study	10	PE beads	100	Kuoppamäki et al. (2021)
Filtration system with sand and biochar	Finland	90–5000	PE, PP	Sand filter: 96 Biochar: 93	Pankkonen (2020)
Biochar amended bioretention cell/rain garden	Sweden	>10	TWPs; identified as PB and PI, PE, PET, PMMA, PS, PVC	>98	Johansson et al. (2024)

EVA: Ethylene-vinyl acetate, PB: polybutadiene, PES: Polyester fibers, PI: polyisoprene

How can microplastics be removed with porous media?

Traditionally, sand and soil have served as the primary filtration media for stormwater treatment, effectively retaining suspended solids (Davis et al., 2009; Zarezadeh et al., 2018). However, the complex composition of stormwater pollutants, coupled with the growing demand for sustainable filtration solutions, has led to increased interest in nature-based materials that offer enhanced sorption capacity and carbon sequestration potential (Ashoori et al., 2019; Mohanty & Boehm, 2014; Ulrich et al., 2017). Among these nature-based materials, biochar has emerged as a promising material for stormwater treatment. Biochar is produced through the pyrolysis of organic biomass under oxygen-limited conditions (Jamaludin et al., 2019). The media is characterized by high porosity, a well-developed internal pore network, and a large surface area, which taken together can enhance water-holding capacity and pollutant removal efficiencies through improved sorption capacity. These beneficial properties, however, are strongly influenced by several factors, including the type of feedstock and the specific pyrolysis conditions, particularly temperature and duration (Brassard et al., 2016).

Compared to conventional sand filters, biochar has demonstrated equal or superior removal performance for various pollutants, including toxic metals such as Cd, Cu, Ni, Pb, and nutrients (Ulrich et al. 2017; Reddy et al. 2014). Additionally, biochar has demonstrated superior retention of MPs. Wang et al. (2020b) reported that biochar achieved a straining efficiency of over 95% for 10 μm PS beads, significantly outperforming traditional sand filters (60–80%). This enhanced performance is attributed to biochar's highly porous morphology, which facilitates the entrapment of MPs. Similarly, Hsieh et al. (2022) found that incorporating a biochar layer within sand filters improved the removal of MPs larger than 1 μm. However, for larger MPs (90–300 μm), biochar and sand filters have exhibited similar removal efficiencies (93% and 96%, respectively; Pankkonen, 2020). These findings indicate that biochar is particularly effective for capturing smaller MPs. Beyond physical entrapment, studies have also highlighted hydrophobic interactions as a key mechanism contributing to improved MP removal (Hanif et al., 2023; Subair et al., 2024). Nevertheless, the ability of biochar to capture a heterogeneous mix of MPs, as typically encountered in stormwater, remains an area for further investigation.

In addition to biochar, other nature-based materials, such as pine bark, have been explored as a sorbent material for stormwater treatment (Björklund & Li, 2015; Cutillas-Barreiro et al., 2014). Pine bark, a by-product of the forestry industry, contains wood cells with both non-polar groups (e.g., fatty acids), and polar oxygen-containing groups (e.g. carboxyl groups; Rowell et al., 2005). This composition enables pine bark to sorb a wide range of both polar and non-polar contaminants. Studies have shown that pine bark effectively sorbs PAHs and phthalates (Björklund & Li, 2014, 2015), the latter of which are commonly used as plasticizers to enhance polymer flexibility (Campanale et al., 2020). While pine bark may effectively remove some micropollutants associated with MPs, its ability to directly remove MPs remains unknown.

Given their ability to carry micropollutants or leach chemical additives over time, MPs present a growing challenge for stormwater treatment. As their abundance in urban environments rises with decreasing particle size, physicochemical interactions with filter media may play a more crucial role than mechanical filtration alone (Frey et al., 1999). This underscores the importance of evaluating porous media with strong sorption capabilities for the effective removal of diverse MP pollutants.

Challenges and considerations in sampling and analysis of microplastics

MPs are ubiquitous in urban environments, requiring targeted sampling across various environmental matrices. Stormwater can be collected during rainfall events to capture suspended MPs, while sediments from settling basins provide insight into accumulated particles. Additionally, urban surface dust sampling can help estimate potential MP loads in stormwater. Sampling methods vary by matrix and include continuous sampling, grab sampling, and on-site water filtration. Given the temporal and spatial variability of MPs, standardized protocols are essential to ensure representative data collection.

For solid matrices such as sediments or road dust, homogenization followed by subsampling is typically used to streamline MP extraction (Masura et al., 2015). However, the heterogeneous nature of MPs presents challenges in both quantification and identification, and no universal extraction method currently exists. Researchers commonly employ a combination of filtration, chemical oxidation, digestion, and density separation to isolate MPs from complex matrices.

Identification and quantification of MPs often rely on advanced analytical techniques, including spectroscopic methods (e.g., Fourier Transform Infrared (FTIR) and Raman spectroscopy), and thermoanalytical techniques (e.g., pyrolysis-GC-MS) (Cabernard et al., 2018; Logemann et al., 2018; Primpke et al., 2017; Song et al., 2015). The choice of method depends on factors such as MP size and whether measurements focus on particle count or polymer mass. Since each technique has inherent size detection limits, pre-fractionation of samples is often necessary. If possible, a two-step complementary approach is recommended: first, a non-destructive spectroscopic method to determine particle counts, followed by a thermoanalytical technique for precise polymer mass quantification.

Ultimately, careful selection of sampling and analytical methods is crucial, as these decisions influence the reported MP types and concentrations. Addressing these challenges is essential for generating reliable data that can inform effective stormwater management strategies.

Method and materials

Monitoring of microplastic pollution in an urban environment

MP pollution was assessed in urban areas of Uppsala, Sweden, a city with approximately 177,000 residents and diverse urban activity (Andersson & Nygren, 2023). The primary aim was to assess MP pollution in urban surfaces, focusing on both MP abundance and composition, to better understand their distribution in urban environments. These findings also inform the selection of representative polymers for laboratory studies, aiding in the development of more effective MP removal techniques. To achieve this, road dust and spider webs were sampled and analyzed for MPs to assess their presence and contribution to urban pollution (**Paper I**). Additionally, road dust was used to create semi-artificial stormwater for controlled pilot-scale experiments, investigating MP transport and retention in biochar beds (**Paper IV**).

Microplastic sampling sites and sample collection

Parking lots in Uppsala urban areas were selected as sampling sites due to their impermeable surfaces and their role as significant contributors to stormwater pollutant runoff (Fuerhacker et al., 2011; Österlund & Fältström, 2023). They also provided safe, accessible locations with relatively uniform vehicle activity, including consistent vehicle types and speed patterns. In **Paper I**, seven parking lots representing different urban functions were examined (see Table 2 for details) to assess MP contamination. Surface road dust and spider webs were collected across these locations. Road dust samples were taken from three sections of each parking lot: drive-in lanes, center lanes, and curb lanes. To ensure comprehensive sampling, three 1 m^2 areas per section were vigorously brushed with a steel brush to loosen particles before collection using a custom-built stainless-steel vacuum device, Dusty (AAU, Denmark). Equipped with a 10 µm stainless steel filter, Dusty facilitated particle collection in steel buckets (Figures 2a, and b). A total of nine samples (9 m^2 per parking lot) were pooled by section.

Spider webs were collected from nearby infrastructural elements, such as lamp posts and road signs (**Paper I**). The webs were carefully removed using wooden sticks and stored in glass vials for further analysis (Figure 2c). This method provided insights into potential airborne MP pollution within the urban catchments.

For **Paper IV**, additional road dust samples were collected from the same commercial parking lots (Table 2) to generate semi-artificial stormwater for controlled experiments on MP transport and treatment in pilot-scale biochar beds. Specifically, grab samples of road dust were taken from curb areas using a metal spoon, and stored in glass containers.

Table 2 Details concerning the sampled parking lots (**Papers I and IV**)

Catchment area	**Activities in the proximity of the parking lot**	**Sample Type Collected**	**WGS84 decimal (lat, lon)**
Recreation	Artificial grass field Gymnasium and Gym Green areas and apartment complexes	Road dust, Spider webs (Paper I)	59.846968, 17.607948
City central	Hotels Railway station Restaurants Concert hall	Road dust, Spider webs (Paper I)	59.860563, 17.646441
Commercial	Shopping mall at Gränbystaden	Road dust, Spider webs (Paper I), Grab samples of road dust (Paper IV)	59.877352, 17.676267
Commercial	Indoor parking in Gränbystaden shopping mall	Road dust, Spider webs (Paper I)	59.877352, 17.676267
Industrial	Building supply stores Vehicle-related industries	Road dust, Spider webs (Paper I)	59.881761, 17.588446
Commercial/industrial	Commercial outlets, like a large furniture store, situated in an industrial area	Road dust, Spider webs (Paper I), Grab samples of road dust (Paper IV)	59.847863, 17.693326
Residential	Low-rise, high-density living spaces	Road dust, Spider webs (Paper I)	59.868779, 17.647817

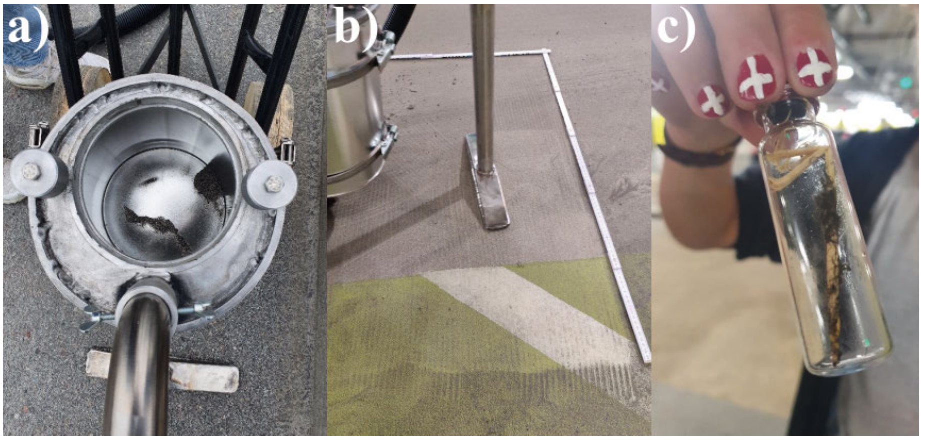

Figure 2 Sampling of road dust via Dusty (a and b) and spider webs (c) in **Paper I**.

Laboratory and pilot-scale studies on microplastic retention in sand, bark, and biochar

A significant portion of this thesis involves laboratory experiments, investigating the removal efficiency of MPs in laboratory-scale beds and pilot-scale horizontal flow filters packed with different porous media. Below are details of the experimental setups, materials, and the experimental execution.

Experimental setups

Identical experimental setups were used in **Papers II and III**. Each setup consisted of duplicate PVC tubes (D = 4.6 cm) with lengths of 25, 50, and 100 cm (Figure 3a). A coarse mesh (0.1 cm mesh size) was installed at both ends (Figure 3b). The filters were packed with porous media: sand in **Paper II** and bark and biochar in **Paper III**.

Figure 3 Photos of a) the horizontal flow filter setup for three filter lengths (L = 25, 50, and 100 cm) and b) the coarse mesh, at filter inlets and outlets.

The pilot-scale experiment (**Paper IV**) used two horizontal flow units (100 × 20 × 45 cm) constructed from 10 mm Plexiglas and packed with biochar (Figure 4). To ensure uniform flow distribution and filtration, the first 10 cm of each biochar bed was filled with crushed rock (8–16 mm, granitic composition), and a 5 cm upper rock layer was added to prevent biochar buoyancy and stabilize the media during stormwater events. Additionally, flow-directing Plexiglas walls (20 × 25 cm) were installed 10 cm from both the inlet and outlet to enhance water infiltration into the media. The primary sampling point was positioned 5 cm from the top at the outlet, allowing continuous sampling under saturated conditions during stormwater events. To enable additional sampling, Plexiglas tubes (20 cm long, 5 cm in diameter) with systematically spaced 0.5 cm perforations were placed across the horizontal length and secured with holders. To prevent biochar leakage, crushed rock was layered around these tubes. Water samples were extracted through metal taps installed on the sides (Figure 4).

Figure 4 Photographs of the biochar bed set up (**Paper IV**) with additional sampling points, which are layered with rock material.

Porous Media

In this study, we used commercially available bark and biochar to construct the porous media filters. While many studies focus on developing and modifying adsorbents to enhance removal efficiency, our approach prioritizes sustainability and accessibility by utilizing readily available products.

The commercial biochar used in **Paper III and IV** was sourced from Vindelkol AB (Sweden) and produced through the pyrolysis of a feedstock predominantly composed of pine (*Pinus sylvestris*), along with smaller proportions of birch, alder, and aspen hardwood. The production process took place at 500°C, over approximately 8–14 hours. Additionally, the pine bark used in **Paper III** was procured from Plantagen (Sweden), while natural sand was obtained from Hasselfors, primarily composed of quartz and feldspars (**Paper II**). The size distributions and material characteristics, such as elemental composition and specific surface area, are presented in **Paper II-IV**. See also image examples of the materials captured by Scanning Electron Microscope (SEM) in Figure 5.

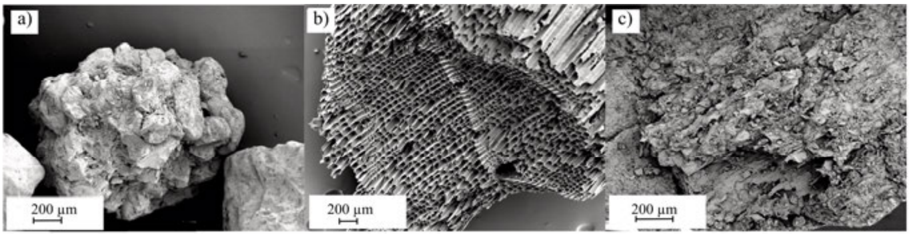

Figure 5 Electron Microscope (SEM) images of the porous media a) sand b) biochar, and c) bark.

Types and properties of virgin microplastics

Throughout the retention studies in **Papers II-IV**, freshly produced "virgin" MPs were used to assess retention based on porous media and MP properties. Most virgin MPs were purchased ready-made (Table 3), but PP and PET fibers and PP fragments used in **Papers II-IV** were manipulated into specific sizes and shapes on-site. The method of introducing virgin MPs in the filter experiments (**Papers II-IV**) varied in MP load, type, shape, size, and application technique (Tables 3 and 4)

Table 3 Information on the virgin microplastics used in the experiment (morphology, particle size, density), as provided by the supplier. † Information collected from μ-FTIR and SiMPle analysis.

MP type	Morphology	Relevant Paper #	Particle size (μm)	Density (g/cm3)	Supplier
PA12	Spherical	II, III	Mean: 25–30	1.020	Goodfellow, England
PA 6.6†	Fragments	IV	Mean: 34	1.14	Microplastic solution, France
PA 6.6 †	Fiber	IV	Width: 41 Length:270	1.14	Microplastic solution, France
PE	Spherical	II, III	Mean: 125	0.94	Sigma-Aldrich, Germany
PET†	Fiber	II	Width: 23 Length:291	1.35	Goodfellow, England
PP †	Fragments	II, III	Median: 63	0.90	Goodfellow, England
PP †	Fragment	IV	Mean: 35	0.90	Microplastic solution, France

PP †	Fiber	II	Width: 28 Length: 241	0.90	Goodfel-low, Eng-land
PS	Spherical bead	III	900	1.05	Goodfel-low, Eng-land

Experimental approaches

To assess the retention of MPs (**Papers II and III**) and the combined retention of MPs and metals (**Paper IV**), systematic sampling of effluent water and filter media was conducted. While **Papers II and III** shared similarities in experimental design, **Paper IV** differed in scale and complexity, leading to variations in sampling methods across studies. The experimental approaches for each paper are described below and are also summarized in Table 4.

Table 4 Parameters for experiment designs in **Papers II-IV**

Parameters	**Paper II**	**Paper III**	**Paper IV**
Porous media	Sand	Bark, Biochar	Biochar
MP shapes	Fiber, spheres, fragments	Spheres, fragments	MPs from stormwater + Added fibers and fragments
MP types	PA, PE, PP, PET	PA, PE, PP, PS	MPs from stormwater: PP>PE>PA>PVC>PS>PET Added: PA6.6, PP
MP load	0.1 g per MP type	0.07 g per MP type (0.5 g of PS)	MPs from stormwater: 62 MPs/L. Added: 258 MPs/L
MP spiking method	Placed in MP-mixing zone (0–2 cm)	Mixed with the porous media in the MP-mixing zone (0–2 cm)	Added to biochar bed inlets per stormwater event
Water matrix	Tap water	Tap water	Semi-artificial stormwater
Flow direction	Horizontal	Horizontal	Horizontal
Flow rate	1 mL/min	5 mL/min	270 mL/min
Experimental duration	1 week	1 week	13.5 weeks
Main analysis	MPs	MPs	MPs and metals
MP extraction water phase	The cumulative effluent	The cumulative effluent	The cumulative effluent after each stormwater event
MP extraction porous media	Total sand media packed in 25, 50, and 100 cm filters, and 0–2 cm of the initial filter media	Total bark packed in one 100 cm filter divided into 10 cm segments.	Not extracted

Laboratory-scale experimental details (Papers II and III)

In **Paper II**, three different filter lengths (25, 50, and 100 cm) were packed with sand and received a continuous flow of tap water at a rate of 1 mL/min for one week, resulting in a total sample volume of approximately 10 L. The total effluent was collected and analyzed for MPs. MPs were introduced at the inlet and consisted of PA and PE spheres, PP fragments, and PP and PET fibers (Tables 3 and 4). At the end of the experiment, the entire sand content of each filter, as well as the agglomerations in the MP-mixing zone (0–2 cm) were extracted and analyzed for retained MPs.

Following the setup of **Paper II**, the sand was replaced in **Paper III** with bark and biochar. The influent tap water flow rate was 5 mL/min, and the effluent was collected over one week, resulting in a total sample volume of approximately 50 L. The total effluent was collected and analyzed for MPs. MPs introduced at the inlet included PS beads, PA and PE spheres, and PP fragments (Tables 3 and 4). At the end of the experiment, bark from one 100 cm filter was divided into 10 cm segments and extracted for MP retention analysis.

Pilot-scale experimental details (Paper IV)

This study differed in scale and complexity. With key modifications including:

Semi-artificial stormwater: created using road dust sampled from curbs in commercial parking lots in Uppsala (Table 2). For each stormwater event, a total mass of 48 g of road dust with 43 L de-ionized (DI) water was applied. The stormwater was assessed for the original content of MPs and metals. Virgin MPs (PA and PP fibers and fragments) were also added (Tables 3 and 4).

Simulated events: Stormwater events were introduced twice a week, with two to three dry days in between. A designed first flush carried 80% of the road dust mass and added virgin MP counts, in 30% of the total event volume (13 L), with the remaining road dust and virgin MP load following in 30 L stormwater.

Environmental stress testing: Biochar beds were tested under three different conditions (Figure 6):

1. Three weeks of normal stormwater conditions.
2. A five-week dry period followed by one event with pure DI-water collected in 6 volume increments, to assess potential pollutant release due to prolonged drying, and then two weeks of normal stormwater conditions.
3. One week of stormwater with 4g/L NaCl addition simulating road salt conditions, followed by two weeks of normal conditions.

Expanded pollutant analysis: In addition to MPs, the study examined the removal of nine metals from stormwater.

The experiment lasted for 13.5 weeks, and stormwater was added twice a week (270 mL/min), except during the dry period (Figure 6). A total of 730 L of effluent was generated over the experiment. Cumulative effluents from each stormwater event (43L) were analyzed for MPs, and influent and effluents were sampled for total and dissolved metals. Unlike **Papers II and III**, no material extraction for MPs was conducted. However, metal analysis was performed at additional sampling points along the biochar beds' horizontal length (5, 50, and 95 cm; Figure 4).

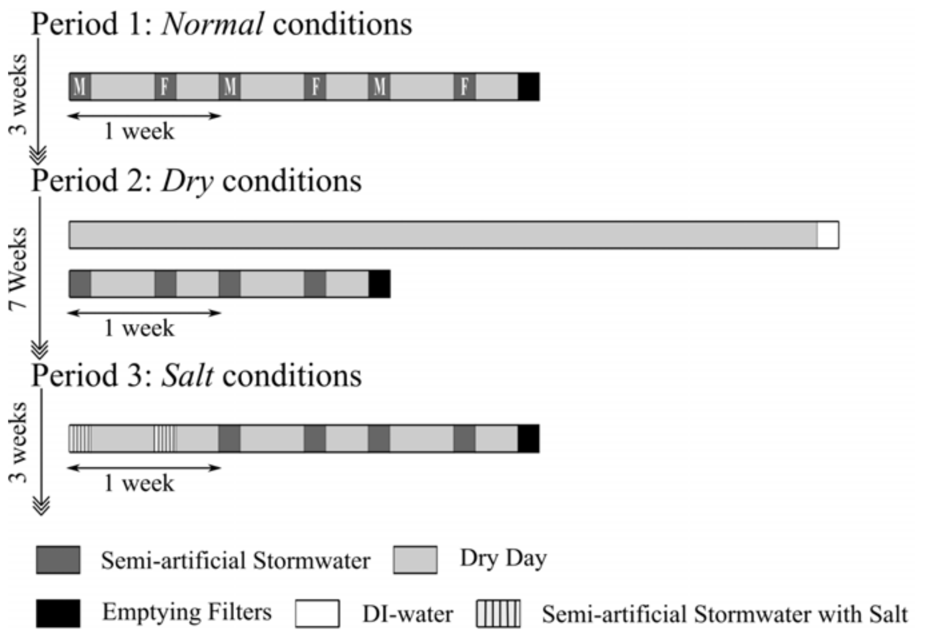

Figure 6 Timeline of the experimental run (**Paper IV**), showing stormwater events with specifications and sampling on Monday (M) and Friday (F) over each week.

Improving microplastic mobility studies through polymer diversity

Most MP mobility and retention studies focus on only one or two polymer types, often relying primarily on PS as a test polymer. However, urban MP pollution is highly heterogeneous, consisting of a diverse mix of polymers, shapes, and sizes. To better reflect this complexity, **Papers II-IV** expanded the scope by incorporating a broader range of polymers (Table 4). However, the methodology in **Paper II** raised concerns about homo- and hetero-aggregation, particularly the potential for fibers to interfere with the transport of other MPs. To address these concerns, **Paper III** focused exclusively on spherical MPs of increasing sizes (25–900 µm) and a single MP fragment, while also reducing the applied MP mass by 30% (Table 4). Despite this, potential oversaturation in filter experiments remained a concern, as high MP concentrations may have induced retention patterns that are more representative of later operational stages when filter clogging becomes more pronounced.

Another critical factor influencing MP behavior is the distinction between virgin MPs used in laboratory studies and aged MPs found in the environment. Naturally occurring MPs undergo weathering and degradation, which alters their physical and chemical properties, ultimately affecting their transport and retention in stormwater treatment systems. To account for this, the final pilot-scale experiment (**Paper IV**) introduced semi-artificial stormwater containing both naturally occurring and virgin MPs at environmentally relevant concentrations (Table 4), minimizing the risk of oversaturation and enhancing the study's real-world applicability.

Importantly, all polymer types used in the laboratory experiments (**Papers II-IV**) were also identified in urban road dust and spider webs (**Paper I**), reinforcing the environmental relevance of the experimental design. By incorporating a diverse range of MPs and considering factors such as aging and aggregation, these studies offer a more representative assessment of MP behavior in stormwater treatment systems, bridging the gap between laboratory research and real-world pollution scenarios.

Microplastic extraction and analysis

The main extraction techniques used across various matrices –including road dust, sand, bark, and effluent water– relied on filtration, density separation, and oxidation (**Papers I-IV**; Table 5, Figure 7). Consistent methodologies for MP extraction and identification were employed, with quantification and identification performed using µFTIR imaging. Data were processed via SiMPle software, enabling a better comparison of findings and a more comprehensive assessment of MP pollution.

Table 5 Overview of applied extraction and analysis methods for **Papers I-IV**

Paper #	Filtration	Sieving and size fractioning	Density separation	Hydrogen peroxide	Fenton reagent	µFTIR imaging	SiMPle software
I	✓	✓	✓	✓	✓	✓	✓
II	✓		✓			✓	✓
III	✓	✓	✓		✓	✓	✓
IV	✓	✓	✓		✓	✓	✓

Filtration and sample size fractionation

The cumulated effluents from the sand, bark, and biochar filter experiments were collected and extracted directly from the water phase by percolating the water through 10 µm stainless steel filters, under vacuum filtration (**Papers II-IV**). The MPs were then resuspended from the stainless-steel filters by sonication in pure ethanol. The liquid was then evaporated under a stream of nitrogen gas, concentrated to a set volume, and stored in 20 mL glass vials.

The road dust was size-fractioned and particles >500 µm were separated from the rest of the dust (**Papers I-V**). After which, the road dust was homogenized and subsampled before further extraction. In **Paper III**, the bark segments were fractioned by wet-sieving the material and separating particles that were smaller or larger than 300 µm. Particles >300 µm were visually inspected, and PS beads (900 µm) were manually picked. Particles <300 µm were subjected to further extraction using density separation and chemical oxidation, as described below.

Density separation

Density separation was applied to separate the MPs from the sand, bark, and road dust matrices (**Papers I-IV**). The density of MPs depends on the type of plastic and therefore the choice of solution used for density separation depends on targeted MP types. A $ZnCl_2$ solution with a set density of 1.4 g/cm^3, was utilized to separate sand and bark from MPs of known densities $\leq$ 1.35 g/cm^3 (**Papers II** and **III**). However, given the unknown MPs residing in the road dust, a sodium polytungstate (SPT) solution with a higher density (1.9 g/cm^3) was used to separate the MPs (**Paper I**; Li et al. 2020; Besley et al. 2017), and $ZnCl_2$ (1.7 g/cm^3) in **Paper IV**. In all papers, the samples and the density separation solutions were mixed into separation funnels and left to settle for 24 hours. The MPs were later separated in the funnel and the sediment fraction was discharged through a bottom valve. In this thesis, the settling and removal cycles were repeated over several days for each study (**Papers I-IV**).

Chemical oxidation

Fenton reagent was applied to extract MPs in bark segments and road dust (**Papers I, III, and IV**). An optimized environment for Fenton oxidation was reached by adding 145 mL of 50% H_2O_2, 65 mL of 0.1M NaOH, and 62 mL of 0.1M $FeSO_4$. To minimize any damaging effects of the exothermic reaction, the oxidation of bark and road dust was conducted in an ice bath, keeping the reaction stable and the temperature of the sample lower than 40 °C **(Papers I, III, and IV**). This minimized potential sample overflow as well as unwanted fragmentation of particles. Additionally, H_2O_2 was utilized to digest the spider webs (**Paper I**). In detail, the spider webs were mixed with 50 mL pre-filtered water, and a 50% H_2O_2 solution was added in 5 mL increments until the samples were digested.

Microplastic identification and quantification

In this thesis, μFTIR was utilized to identify MPs extracted from road dust (**Papers I and IV**) and spider webs (**Paper I**) and from effluent water samples and sand and bark media (**Papers II-IV**). In all papers, the extracted concentrated ethanol-MP suspensions were deposited on 13x2 mm zinc selenide optical windows (Crystran, UK) and mounted in a micro compression cell (Pike Technologies, USA). The number and chemical composition of the MPs deposited on windows were determined using a Cary 620 FTIR microscope coupled with a Cary 670 IR (**Paper I**) and Cary 660 IR (**Papers II-IV**) spectrometer (Agilent Technologies, USA). The complete functional area of the zinc selenide window underwent scanning with a 15x Cassegrain objective, coupled with a mercury cadmium telluride (MCT) detector equipped with a 128×128 FPA (**Paper I**) and a 64×64 FPA (**Papers II-IV**) detector providing a 5.5 μm pixel resolution. The complete area of the window was analyzed in transmission mode with 120 background scans. All samples were scanned with spectral ranges appropriate for MP analyses, 3750–850 cm^{-1} (**Paper I**) and 3750–950 cm^{-1} (**Papers II-VI**), at 8 cm^{-1} resolution with 30 (**Papers I and IV**) or 16 (**Papers II and III**) coadded scans (Olesen et al., 2019; Simon et al., 2018).

Data handling and analysis

Analyzing and identifying particle spectra from μFTIR-imaging can be time-consuming and it requires expertise from the operator. It becomes extra difficult when identifying spectra of environmental MPs, as changes in the chemical structure of the polymer may appear (Lusher et al. 2020; **Papers I and IV**). To minimize human sources of errors, semi-automated analyses of the imaging spectra were further processed in siMPle v.1.3.1β (**Papers I-IV**; Primpke et al., 2020). SiMPle (Systematic Identification of MicroPlastics in the Environment) is a freeware software developed by Aalborg University (AAU, Denmark) and the Alfred-Wegener-Institute (AWI-Helgoland, Germany) which enables pixel-by-pixel matching of spectra from IR images with a reference library containing spectra of various standard plastics and organic materials (Primpke et al., 2017; Primpke et al., 2018). In **Papers II-IV** the spectra obtained for the standard MPs used in the experiment were also added to the reference library. Utilizing SiMPle, the MPs in spider webs, road dust, porous media, and effluent water samples were identified and quantified (**Papers I-IV**). Additionally, the software provided an estimation of particle mass, based on an assumption of particle thickness, elliptical shape, and MP density (SiMPle, 2022). Simultaneously, data of the MP's major dimension was provided as the longest distance between the pixels of the matched particle, while the minor dimension was derived assuming an elliptical shape of each particle. In **Papers I, II, and IV** fibers were classified as having a ratio of major and minor dimensions higher or equal to 3 (Vianello et al., 2019).

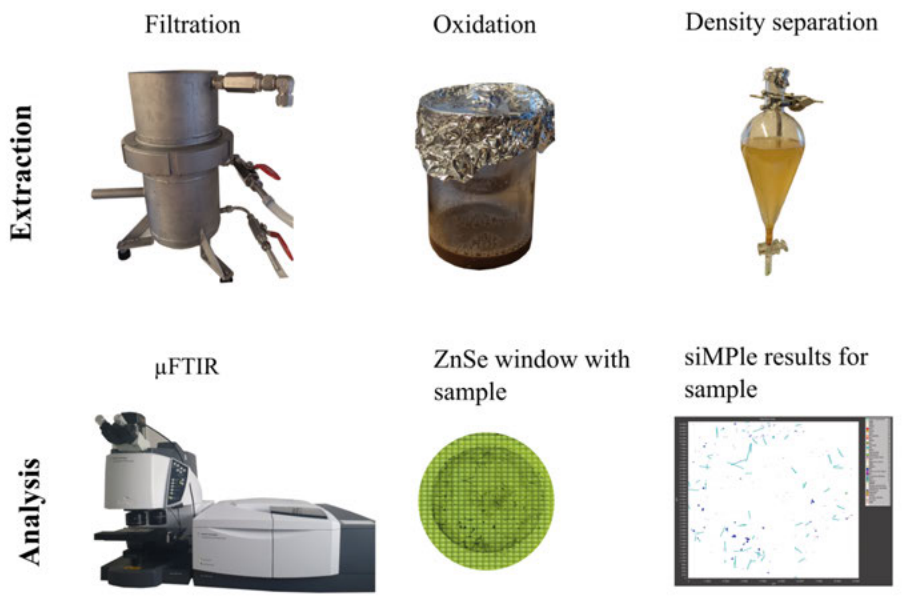

Figure 7 Photos of filtration-unit, oxidation, and density separation during microplastic extraction, and photos of the analysis instrument (μFTIR), with a captured microscope image of an extracted microplastic sample, along with its 2-D image in siMPle analysis.

Analysis of dissolved and total metals (Paper IV)

Throughout **Paper IV**, the influent and effluent stormwater was analyzed for nine metals (Fe, Mn, Pb, Cd, Cr, Co, Cu, Zn, and Ni) via Inductively Coupled Plasma Mass Spectrometry (ICP-MS; Thermo Fischer Scientific ICAP Q) with a FAST sample introduction system (Elemental Scientific) and He as collision gas. Dissolved metals were analyzed after filtration of water samples with sterile 0.45 μm PES syringe filters (VWR). All samples were stored in 15 mL metal-free centrifuge tubes (VWR) and acidified with 1% nitric acid (70% HNO_3, ≥99.999% trace metal grade, Sigma-Aldrich) before analysis.

Limitations in analytical methods

While this study provides valuable insights into MP retention and transport in urban environments, several limitations must be acknowledged. One key aspect is the presence of tire wear particles (TWPs) in road dust samples. Although not analytically confirmed, TWPs likely constituted a significant fraction of the collected material (**Papers I and IV**). Moreover, their presence in samples analyzed via μFTIR (**Papers I and IV**) may have influenced the results, potentially obstructing polymer detection by absorbing light. Consequently, while TWPs are a major contributor to urban MP pollution, they could not be reliably analyzed using the available methods and were therefore excluded from the scope of this thesis.

A similar challenge arose with biochar samples (**Papers III and IV**), which could not be analyzed using FTIR. This limitation underscores the inherent complexity of evaluating MP retention in filtration systems that incorporate biochar media.

Another fundamental limitation, well known within MP research, is the time-consuming procedure of MP extraction and analysis. The labor-intensive processes inevitably constrain the amount of data that can be generated, making it challenging to establish strong statistical relationships. However, this limitation is not unique to this thesis; it reflects the broader state of MP research. Future advancements should focus on refining and standardizing extraction and analytical methods to enhance comparability across studies while also improving efficiency to allow for larger-scale investigations.

Main findings and discussion

Microplastics in road dust and spider webs from urban areas (Papers I and IV)

This thesis examined MP loads in road dust collected from urban parking lots and analyzed polymer distribution patterns based on surrounding activities. By studying impermeable surfaces, this approach highlights potential MP sources for transport via wind or stormwater, offering insights into accumulated pollutant loads in urban areas.

Microplastic abundance

Consistent with previous MP studies, the analysis of road dust from different parking lots (**Paper I**) revealed significant variation in MP abundance, ranging from 5.0 to 5,000 counts per gram of road dust, with a median value of 160 counts per gram in the 10–500 µm size range. The eight most abundant polymers across all sampled parking lots were PU > PP > PET > PMMA > PE > PS > PA and > cellulose acetate.

Since the artificial stormwater used in **Paper IV** was generated from grab samples of road dust collected at the commercial parking lots, a comparison with the findings from **Paper I** provides valuable context. In **Paper I**, outdoor commercial parking lots exhibited MP abundances ranging from 4 to 300 counts per gram of road dust, with PP (32–79%) as the dominant polymer, followed by PE. This polymer distribution aligns well with the results from **Paper IV**, where MP extraction and analysis of grab samples revealed an MP concentration of 56 counts per gram of road dust. Here, PP accounted for 83% of the detected MPs, followed by PE (13%), with smaller proportions of PA, PVC, PS, and PET (6%). Note that while PU was detected in commercial parking lot samples in **Paper I**, it was absent in the grab samples analyzed in **Paper IV**. This highlights differences in MP distribution, likely caused by the inhomogeneous content of road dust samples.

Another notable finding in **Paper I** was the detection of airborne PET fibers in spider webs, with MP concentrations ranging from 2,500 to 500,000 counts per gram (10–500 µm) and estimated masses between 40 and 590,000 µg/g. These results align with Goßmann et al. (2022), who reported MP abundances of 11,400–108,000 µg/g in urban spider webs, reinforcing the role of webs as passive samplers of airborne pollution.

The widespread presence of airborne PET fibers has been reported previously (Dris et al., 2015; Treilles et al., 2021), with studies showing higher indoor concentrations, particularly for fibers, than in outdoor environments (Perera et al., 2022, 2023). We propose that the fibrous morphology of PET facilitates its ability to become airborne and enhances its likelihood of being captured in spider webs, despite its relatively high density.

Catchment Types and Spatial Trends

One of the key findings of **Paper I** was the stark contrast in MP loads between indoor and outdoor commercial parking lots. Road dust from an indoor parking lot contained 31 times more MPs by count and 9.4 times more MPs by mass compared to outdoor parking lots. The dominant MP type in indoor road dust was PU, which was traced back to floor coatings in the parking lot. Although the sampling method (using a metal brush to loosen dust) may have exaggerated PU presence, this finding underscores the potential for indoor environments as MP sources.

Contrary to earlier findings suggesting that commercial and industrial areas release more MPs than residential areas (Liu et al., 2019), our study found no statistically significant differences in MP concentrations across catchment types (Table 2). However, slight variations in polymer distribution were observed. For instance, in an industrial parking lot (**Paper I**), MPs were predominantly acrylic polymers, likely originating from automobile-related workshops in the area.

Similarly, spatial sampling across parking lots did not reveal statistically significant differences in MP abundance, yet certain trends emerged. Curbside samples contained notably higher MP mass than those collected from the middle or entry lanes of parking lots (**Paper I**). Median MP masses were 26 µg/g in curb samples, 17 µg/g in middle-lane samples, and 6 µg/g in entry-lane samples. A comparable pattern was observed in **Paper IV**, where the average MP mass in curb grab samples was 31 µg/g, reinforcing our conclusion that larger MPs tend to accumulate along curbs.

Microplastic retention in sand, bark, and biochar: laboratory and pilot-scale experiments (Papers II-IV)

Findings from **Paper I** confirm that MP pollution is both heterogeneous and abundant in urban environments, highlighting the need for continued research on MP remediation strategies. A key unanswered question is how the diversity of MP pollutants–varying in polymer type, shape, and size–affects their removal in filtration systems. In **Papers II-IV**, we explore how different porous media capture MPs in laboratory-scale and pilot-scale experiments, with a particular focus on MP characteristics and the influence of environmental stressors (**Paper IV**).

Retention efficiencies of microplastics in porous media

This thesis demonstrates consistently high MP removal efficiency across all studies (**Papers II-IV;** Figure 8), confirming the effectiveness of various porous media for MP retention. Horizontal flow filters using sand, bark, and biochar achieved >99% retention of total MP mixtures, including most individual MP types (**Papers II and III**).

A few exceptions were observed: one sand filter replica in **Paper II** exhibited >97% removal of PE, while a bark filter replica in **Paper III** exhibited >97% removal of PA, PE, and PP MPs. Notably, these cases occurred in filters measuring 25 cm in length. Overall, MP retention in sand filters (**Paper II**) was comparable to that in biochar and bark filters (**Paper III**). However, **Paper III** operated at a flow rate five times higher than that in **Paper II**, suggesting that bark and biochar filters effectively retained MPs even under higher flow conditions. This is particularly relevant, as increased MP mobility has been linked to higher flow rates (Subair et al., 2024). The superior retention of bark and biochar may be attributed to their ability to entangle MPs, a phenomenon observed in previous studies (Wang et al., 2020b). Nonetheless, direct comparisons between **Papers II and III** remain challenging due to differences in MP application methods (Table 4).

Retention trends also reflect on the role of filter length or, conversely, hydraulic residence time. In **Papers II and III**, the highest MP counts in total effluents were observed in the 25 cm and 50 cm filters across all media types (biochar, bark, and sand), suggesting that the longer 100 cm filters provided enhanced retention under the same flow rate. This aligns, to some extent, with findings by Subair et al. (2024) who observed that MP retention in smaller-scale vertical biochar filters (ranging from 1.5 to 6 cm), was directly influenced by filter height under a constant flow rate. However, the release of MPs from biochar beds after prolonged drying (**Paper IV**), as well as MP accumulation at distances of 80–90 cm in 100 cm bark filters (**Paper III**), indicate that preferential flow pathways can develop regardless of filter length, and should be carefully considered in future system designs.

In **Paper IV**, the total retention of virgin MPs throughout the full experiment (*Normal*, *Dry,* and *Salt* periods) was as follows: PP fragments were retained at levels exceeding 98% across both biochar bed replicates, while PA fragments showed lower retention, at >83% and >91% (See also Figure 8 for removal efficiencies across individual periods). In contrast, PP and PA fibers exhibited similar high retention above 99%. Road dust-derived MPs were also efficiently removed, though with some variation depending on polymer type: PE was retained at >94% and 97%, PET at >99%, PS at >92 or 100%, whereas PVC showed the lowest retention, ranging from >33% to 68%. These findings highlight the variability in MP retention across polymer types and emphasize the need for further research into the factors influencing retention efficiency, such as polymer characteristics and filter design.

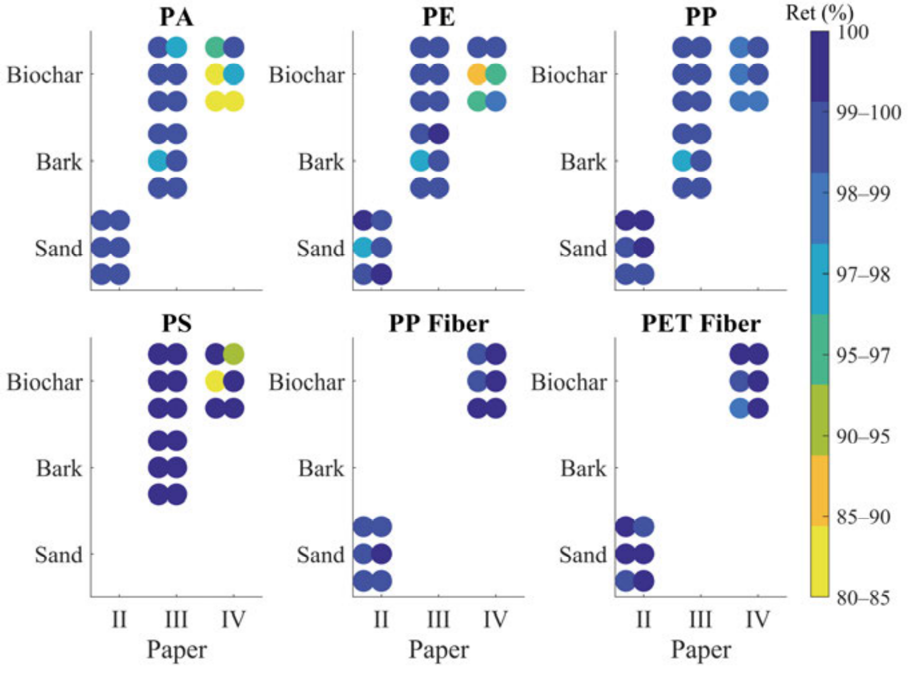

Figure 8 Retention of selected polymers across different materials and papers. Each panel shows the retention efficiency for a specific polymer, plotted by paper (x-axis) and material (y-axis). Retention values are color-coded by percentage, and grouped into bins from 80% to 100%. Data points represent n=6 effluents in Paper II (sand media; 25, 50, and 100 cm), n=12 in Paper III (bark and biochar media, same filter lengths), n=6 in Paper IV (biochar bed replicates sampled over *Normal*, *Dry*, and *Salt* periods). While the data is plotted together for visual comparison, the experimental conditions, and MP characteristics (e.g., shape or size) may differ between papers. Only the polymer types found across all papers are presented in the figure.

Microplastic retention profiles

Understanding how MPs are retained and distributed within filter media is crucial for evaluating filtration efficiency and long-term performance. In **Paper II**, MP extraction from the sand media revealed that 62–85% of the MP mixture was retained within the initial 0–2 cm of the filters (Figure 9), presumably due to agglomeration. Further analysis showed that 18–38% of MPs moved horizontally through the filter, with distribution observed at distances of 2–25 cm, 2–50 cm, and 2–100 cm from the inlet (Figure 9). A similar pattern emerged in **Paper III**, where most MPs were retained in the first 0–10 cm of a 100 cm bark filter, while the second highest MP concentrations were found in the final segments (80–90 cm; Figure 9).

The high MP accumulation in the initial layers can be partly attributed to the initial placement of virgin MPs in the 0–2 cm section of the filters (**Papers II and III**; Table 4), which, combined with agglomeration (observed in **Paper II**), likely limited MP mobility and enhanced retention. This trend aligns with long-term filtration observations, where MPs naturally accumulate in the initial sections due to clogging at the filter inlet. For instance, Lange et al. (2023) reported that in nine stormwater filtration systems, the highest MP accumulation occurred within the initial 0–5 cm of the filter layers.

These findings highlight the importance of considering both initial retention mechanisms and the potential for deep-layer accumulation when designing and maintaining filtration systems to optimize MP capture and minimize breakthrough.

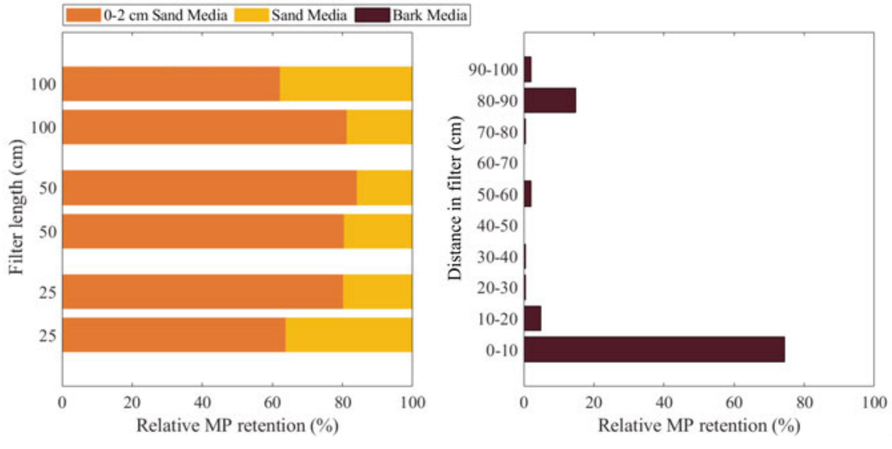

Figure 9 The percentual distribution of all MP counts retained in a) the 0–2 cm (MP-mixing zone) and in the remaining sand media 2–25, 2–50, or 2–100 cm of the duplicate filters in **Paper II**, and b) in 10 cm bark segments 0–100 cm of one filter in **Paper III**. The figure is modified from **Papers II and III.**

Impact of microplastic shape, size, and type on retention

In the experimental work presented in this thesis, we observed high retention of MPs across **Papers II-IV**, as previously discussed. However, certain trends emerged, suggesting that the retention of MPs could be influenced by their shape, size, and polymer type. The following section synthesizes the key findings regarding these factors in the laboratory- and pilot-scale experiments (**Papers II-IV**).

As fiber-shaped MPs have been found in stormwater, and identified in **Paper I,** it is promising to showcase the overall high retention of fibers found in **Papers II and IV**. **Paper II** demonstrated that PET and PP fibers were retained over 99.8% across all filter lengths, a trend confirmed in **Paper IV**, where PA and PP fibers also exhibited retention efficiencies above 99%. The high retention of fibers appears largely size-dependent, with minimal breakthrough observed. Figure 10 further highlights the reduced breakthrough of MPs with increased elongation. However, it is important to note that the small width of fibers may promote their mobility, depending on their orientation during transport.

Size is another critical factor that influences MP retention. In **Papers II and III**, the smallest MPs (PA, 25–30 μm) were the most prevalent in the effluent, suggesting a preference for smaller spherical shapes over fragments and fibers in terms of MP breakthrough. This size-dependent retention aligns with findings from **Paper III**, where larger spherical PS beads (900 μm) were entirely retained in bark and biochar filters. These observations are not only consistent with vertical filtration systems (Liu et al., 2020) but are further supported by the trends seen in our pilot-scale biochar beds (**Paper IV**). In **Paper IV**, we observed similar size-related retention behaviors, with statistical analysis ($p < 0.05$) confirming significant differences in MP sizes from influent versus effluent water samples. Notably, the size distributions of MPs in the effluents of **Paper IV** evolved over time, with a trend toward smaller MPs in the effluent as the experiment progressed. This improvement is likely to be due to filter clogging, which enhances the capture of larger MPs and increases overall filtration efficiency. In Figure 10, the length and width of all MPs found in experiment effluents are compared to the dimensions of the MPs that were introduced throughout each experiment (**Papers II-IV**). This comparison further supports the previous discussion, demonstrating that the likelihood of MPs passing through the filters increases as their size and elongation decrease.

Distinguishing removal efficiencies based solely on polymer type presents challenges, as variations in polymer type often coincide with differences in shape and size (**Papers II and III**). However, **Paper II** provides insights into the role of polymer density by comparing the retention of PET and PP fibers of similar dimensions. High-density PET fibers (1.35 g/cm^3) exhibited greater retention near the filter inlet, with 96% remaining in the MP-mixing zone of sand filters, and were detected in only two out of six effluents. In contrast, lower-density PP fibers were more mobile, appearing in five out of six effluents and showing retention throughout the sand material at depths of 2–25 cm, 2–50 cm, and 2–100 cm (Figure 9). These results suggest that PET fibers' higher density facilitated their retention near the filter entrance, whereas the lower-density PP fibers exhibited increased horizontal mobility. This finding challenges previous vertical column studies (Chrysikopoulos & Syngouna, 2014), which linked increased particle density to greater mobility. As such, we suggest that the horizontal flow system used in **Paper II**, operating perpendicular to gravity, may have enhanced PET fiber retention compared to vertical column setups.

To further isolate the effect of polymer type, **Paper IV** examined PP and PA fragments of similar sizes (Table 3). Despite their comparable dimensions and morphologies, PA exhibited lower retention efficiencies than PP, particularly at the start of the experiment. While MP concentrations in the effluent decreased over time, the higher proportion of PA fragments in the effluent suggests that factors beyond physical entrapment played a role in their retention. Specifically, the polarity of MPs may have influenced their interactions within the biochar beds. We propose that the biochar's chemical properties, particularly hydrophobicity, favored the retention of non-polar MPs, thereby contributing to the observed differences in retention between PA and PP fragments.

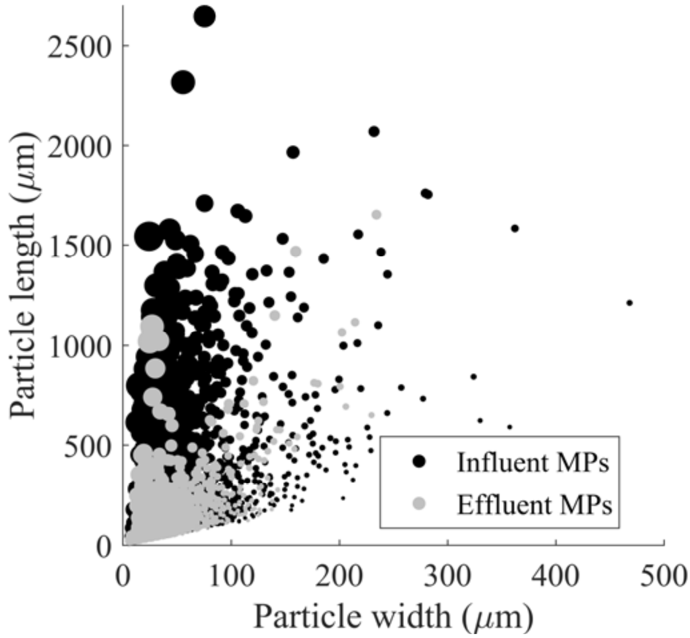

Figure 10 Width and length dimensions of MPs in influents and effluents across all laboratory and pilot-scale experiments (**Papers II-IV**). Dot sizes correspond to the particle elongation factor, with larger dots indicating greater elongation. Note the scale difference between x-and y-axes, and that the figure does not represent MP concentrations.

Expanding retention studies with simulated environmental conditions

Understanding MP retention under real-world conditions requires bridging laboratory experiments with environmental complexity. This thesis expands MP retention research by integrating simulated environmental factors into controlled experiments in **Paper IV**. By incorporating stressors such as drying periods and road salt exposure, we enhance the applicability of laboratory findings to real-world stormwater management (see Figure 6 for a reminder of the experimental execution).

Effects on microplastic retention and mobility

Following three weeks of stormwater exposure, pilot-scale biochar beds in **Paper IV** underwent a five-week drying period before rewetting, after which a reduction in pH from neutral to approximately 5 was observed, accompanied by a yellow-tinted effluent. This was likely due to Fe^{2+} oxidation and consequent $Fe(OH)_3$ precipitation, an acid-generating reaction. These findings demonstrate how environmental conditions, such as drying and rewetting cycles, can alter the chemical environment within filter units, potentially affecting MP retention and mobility.

Results from **Paper IV** also indicated that prolonged drying induced physical changes in the biochar beds, as observed upon rewetting, when MP extraction from the first two effluent volume increments revealed a significant release of MPs, particularly in one replicate. This surge in MP release correlated with turbidity spikes, indicating that structural alterations within the biochar media may have temporarily facilitated particle movement. However, turbidity stabilized within two subsequent stormwater events, suggesting that the changes gradually diminished as the biochar beds regained stability. These findings highlight that prolonged drying may alter biochar structures, creating temporary pathways that facilitate MP transport.

Beyond these structural changes, the study revealed variations in MP retention over time, particularly in terms of polymer distribution. Under normal conditions, non-polar MPs, such as PP, were preferentially retained. However, this selectivity diminished following pH reductions and salt exposure. This shift suggests that electrostatic interactions could have played a role in MP retention. Under neutral conditions, both biochar and MP surfaces were likely negatively charged, leading to repulsion. We suggest that, as pH decreased, this repulsion weakened, thereby enhancing the retention of both polar and non-polar MPs. Furthermore, the presence of Na^+ and H^+ ions may have further influenced MP-biochar interactions, reducing the initial polymer selectivity and altering retention dynamics.

These results highlight the interplay between physical and chemical factors in MP retention. While short-lived structural changes can briefly impact MP transport, long-term retention is further influenced by environmental conditions.

Exploring the role of microplastics in metal mobility

MPs are known to act as potential vectors for metals, with their polarity influencing metal sorption capacity (Brennecke et al., 2016). Given the preferential removal of non-polar MPs observed in **Paper IV**, this becomes an important factor to consider. While previous studies suggest that MPs, particularly polar types such as PA, can enhance metal mobility due to their functional groups (Liu et al., 2021), our analysis did not reveal a direct positive correlation between MPs and effluent metal concentrations in the pilot-scale experiment. Instead, environmental stressors such as salt exposure and prolonged drying played an important part in shaping metal retention dynamics. Periods of prolonged drying led to declining metal retention efficiency, particularly for Mn, Co, and Pb, likely due to increased metal solubility at lower pH and the desorption of metals from Fe-oxide surfaces. Similarly, road salt exposure influenced metal speciation by promoting ion exchange, where Na^+ likely displaced adsorbed metals (e.g., Co, Cu, and Ni), leading to increased dissolved metal concentrations in the effluents.

Our findings suggest that while MPs may influence metal mobility in certain environmental conditions, other factors, such as pH shifts and competitive sorption dynamics, are more dominant drivers of metal retention and release in biochar beds.

Conclusions

MP pollution has become a pervasive challenge in urban environments, with stormwater playing a crucial role in transporting MPs to aquatic ecosystems. This thesis explores MP sources, distribution, and mitigation strategies, providing a comprehensive analysis of their behavior in urban settings and evaluating the efficiency of filtration-based removal techniques. Through a field study and controlled laboratory experiments, this research enhances our understanding of MP retention mechanisms and highlights the complexities associated with stormwater treatment. The thesis was guided by three key research questions, with the findings summarized below:

1. What types and abundances of MPs can be identified in urban surfaces and surrounding air in parking lots in Uppsala, Sweden?

The findings reveal that MP pollution is both widespread and highly variable, with the highest concentrations detected in indoor parking lots. Airborne MPs, primarily PET fibers, were captured in spider webs, highlighting the role of atmospheric deposition. The results indicate that road dust serves as significant MP reservoirs, contributing to their transport through urban runoff and stormwater pathways. These insights underscore the importance of targeted mitigation strategies and improved stormwater management to address MP pollution in urban environments.

2. How effective is MP removal in horizontal flow filters using sand, biochar, and bark materials, considering variations in MP size, shape, and type?

Experimental evaluations of sand, biochar, and bark media demonstrated high MP removal efficiencies, often exceeding 99%. However, retention varied with particle size, shape, and polymer type, with smaller and lower-density MPs exhibiting greater mobility. Fibers showed high retention due to their elongated shape, while polymer properties influenced filtration performance. Biochar beds, in particular, exhibited a preferential removal of non-polar MPs, suggesting a role for polarity-based retention in biochar-based stormwater treatment.

3. How do environmental stressors, like dry periods and road salt, affect the efficiency of pilot-scale biochar beds in removing MPs and metal pollutants from stormwater?

Environmental factors such as drying periods and road salt exposure influenced biochar bed performance. Drying altered biochar's structural properties, leading to temporary MP release upon rewetting, while pH shifts affected metal retention. Road salt exposure modified ionic interactions, impacting filter efficiency. Despite these challenges, biochar beds showed resilience over time, with retention improving as filtration progressed. These findings highlight the need for long-term studies to assess filtration stability under real-world conditions.

By addressing these three research questions, this thesis advances our understanding of MP pollution in urban environments and provides insights into potential mitigation strategies. The findings emphasize the importance of integrating MP remediation techniques into urban planning and stormwater infrastructure to reduce plastic pollution. While filtration-based techniques show great promise, continued innovation and long-term monitoring are essential to ensure their effectiveness and sustainability across diverse environmental contexts.

Future research and outlook

In many urban environments, stormwater is still discharged directly into surrounding ecosystems without treatment, allowing pollutants such as MPs to enter aquatic ecosystems. As urbanization continues and urban pollution intensifies, implementing stormwater management strategies has become increasingly important. While this thesis offers valuable insights into MP mitigation through filtration-based techniques and nature-based media, several areas warrant further investigation to optimize these systems for real-world application.

A key research priority is to develop more realistic approaches for MP retention studies. Current laboratory studies often rely on a limited set of MP types that do not reflect the wide variation in shape, size, and polymer composition observed in urban areas, as demonstrated in this thesis. Incorporating a broader range of MPs, including aged and weathered particles, would provide a more accurate representation of real-world conditions. Additionally, using environmentally relevant MP concentrations will improve the scalability and practical relevance of laboratory findings.

Environmental variability is another critical factor that deserves more attention. The results presented in this thesis demonstrate that seasonal conditions, such as drying periods or the use of road salt, can influence filter performance. As climate change is expected to intensify droughts, extreme rainfall, and other unpredictable weather patterns, future research should examine how these factors affect the stability and effectiveness of filtration systems. This includes exploring the physicochemical mechanisms behind MP retention, such as the influence of pH, ionic strength, and surface charge interactions. A more detailed understanding of these processes, particularly in relation to biochar, would strengthen our ability to predict long-term filter performance under changing environmental conditions.

Moreover, while this thesis highlights the effectiveness of nature-based filters, limitations in analytical methods present challenges to fully assessing their performance. For instance, the presence of TWPs in road dust complicates MP detection, and the inability to analyze biochar material using µFTIR limits our understanding of MP retention patterns. For future research, we suggest combining current methods with complementary techniques such as GC-

MS analysis, to aid in the detection of TWPs and MPs retained in biochar material. Lastly, the time- and labor-intensive nature of MP extraction and analysis remains a major barrier to large-scale research. These constraints limit the volume of data that can be collected and reduce comparability across studies. Improving and standardizing extraction protocols and analytical techniques should be a key focus moving forward to ensure efficiency, consistency, and reproducibility.

By addressing these methodological and environmental challenges, future research can contribute to more reliable and effective stormwater treatment solutions. Integrating realistic conditions, refining analytical approaches, and focusing on long-term system performance will be essential for translating laboratory insights into practical, real-world applications.

Populärvetenskaplig sammanfattning

Mikroplastföroreningar har blivit en av de mest omdiskuterade miljöfrågorna de senaste åren, då de har identifierats i allt från djuphav till fjäll och till och med i livsmedel och dricksvatten. Särskilt i stadsmiljöer, är föroreningen utbredd, där plast används i en mängd olika produkter och material. En viktig transportväg för mikroplaster till naturen är dagvatten, det vill säga regnvatten och smältvatten som rinner av från vägar och bebyggda ytor. Mikroplaster-sprids via luft, vatten och mark och kan tas upp av organismer, vilket kan få negativa effekter på ekosystem och hälsa. Trots att dagvatten är en betydande spridningsväg för mikroplaster, behandlas endast en liten del av dessa vatten innan det når sjöar och vattendrag. Denna avhandling har undersökt både förekomsten av mikroplaster i stadsmiljöer och hur vi kan minska deras miljöpåverkan genom att utveckla hållbara filtreringslösningar.

För att kartlägga mikroplastförorening i Uppsala samlades prov från vägdamm och spindelnät på olika parkeringsplatser i staden. Resultaten visade att mikroplaster var vanligt förekommande i alla undersökta miljöer, men att koncentrationerna varierade kraftigt. Särskilt inomhusparkeringar hade höga halter av mikroplaster, där en stor del bestod av polyuretan, vilket kan hänföras till golvbeläggningar. Förutom markbundna mikroplaster analyserades även spindelnät för att undersöka hur plastpartiklar sprids via luften. Spindelnätsproverna visade sig vara effektiva för att påvisa luftburna mikroplaster, och det vanligaste materialet som påträffades var polyester fibrer. Det här tyder på att mikroplaster inte bara transporteras via vatten utan även sprids genom luften och därmed kan falla ned och ansamlas i nya miljöer.

Att identifiera föroreningar är bara ett första steg – en stor del av min forskning handlar om hur vi kan rena stadens dagvatten från mikroplaster innan det når våra vattendrag. För detta genomförde jag laboratorieförsök med filter som innehöll sand, bark och biokol. Till skillnad från många tidigare studier, där man ofta testar enstaka plasttyper, använde jag en blandning av mikroplaster för att bättre spegla verkliga förhållanden. Resultaten visade att alla filtertyper kunde avskilja över 97 % av mikroplasterna, med en total reningsgrad på över 99 %. Biokol, som tillverkas av förkolnat organiskt material, visade sig dessutom ha en selektiv förmåga att fånga upp icke-polära plaster som polypropen bättre än polära plaster som polyamid. I övrigt visade sig fibrer vara de partiklar som fastnade bäst i filtren, medan vissa mindre partiklar hade en högre rörlighet och var svårare att fånga upp.

För att undersöka hur filtren fungerar i verkliga förhållanden genomfördes tester i större skala, där filtren utsattes för miljöpåfrestningar som längre perioder utan vatten och tillförsel av vägsalt. Resultaten visade att filtren behöll sin höga effektivitet, men att vissa förändringar skedde. Vid långvarig torka kunde mikroplaster tillfälligt frisättas igen när filtret blev blött på nytt, och vägsalt påverkade hur vissa metaller fastnade i filtren. Detta visar att filtrens långsiktiga funktion påverkas av omgivande förhållanden, och att det behövs mer forskning för att optimera deras användning i verkliga dagvattensystem.

En viktig slutsats från denna forskning är att mikroplaster är en omfattande förorening i stadsmiljöer och att de ackumuleras i vägdamm och återfinns i luft. Samtidigt finns det effektiva metoder för att minska spridningen, särskilt genom filtreringssystem baserade på naturliga material. Dessa filtreringssystem kan integreras i dagvattenhanteringen för att minska plastens inverkan på våra vattenekosystem. För att utveckla ännu bättre lösningar behövs fortsatt forskning kring hur mikroplaster, metaller och andra föroreningar samverkar i dagvatten– och hur vi kan designa mer hållbara system för att minska deras påverkan på miljön, och speciellt under verkliga förhållanden.

Acknowledgements

As I write these final words of my thesis, it is hard to believe that four years have passed since this journey began. In many ways, it feels like a lifetime, and yet, at the same time, as if I have only just begun. Throughout the years, I often imagined that by the time I reached this point, I would have most of the answers. But if this journey has taught me anything, it is that the more you learn, the more questions arise. I think that is part of the beauty of science. And while parts of me are understandably tired, I am glad to say that my curiosity is still very much alive. For that, I owe thanks to the many people who have helped nurture it along the way.

First, to my main supervisor, ***Sahar Dalahmeh***. Thank you for the opportunity to pursue a PhD and for your guidance throughout. Your attention to detail has been invaluable to my work, and I am truly grateful for the lessons learned along the way. I especially appreciate your patience during our road dust sampling expedition when I managed to lock both the car keys and my phone inside the car, leaving us stranded in the heat. Thank you also for assembling such an extraordinary team of supervisors. ***Roger Herbert***, having you first as a teacher during my Master's and then as a supervisor has been a privilege. Your clarity of thought, commitment, and steady support have been instrumental. The thoughtful gesture of leaving a homemade jar of jam on my desk after I published my first paper remains one of my fondest memories. ***Ann-Margret Strömvall***, your enthusiasm for research and your dedication to learning and sharing knowledge are truly admirable. You set a high standard in academia, and your encouragement has made the idea of staying in research all the more appealing. ***Jes Vollertsen*** and ***Claudia Lorenz***, thank you for generously sharing your knowledge and resources. Visiting you and your team in Aalborg was one of my fondest experiences during this PhD journey. Thank you for always making time for my many questions, for your expert insights, and for welcoming me into your group with such generosity.

Alongside my supervisors, I have also been fortunate to be part of a wider academic community. At the beginning of my PhD, I started a microplastic journal club, hoping to connect with other students on the same journey. Over the years, people have come and gone, but the core team has remained. A heartfelt thank you to everyone who has contributed to our discussions, and

especially to ***Glenn***, ***Maria***, and ***Elly***. It has been a pleasure to share these moments with you. Outside of our meetings, many others have helped shape my PhD experience. I want to express my sincere gratitude to ***Lucian***, my PhD buddy from Denmark, for your invaluable kindness and support over the years. Thank you for the endless amounts of chocolate, for helping me figure out the FTIR instrument, and for our cathartic catch-ups. GG, my friend.

I am also grateful to ***everyone*** of my colleagues at Uppsala University, who helped make everyday life more enjoyable. Whether through kind conversations over fika or shared moments in the lab, you brightened many long days. Also, I could not have asked for better office mates. ***Christoffer***, thank you for playing silly games with me and for helping me in my stubborn battle with MATLAB. ***Emma***, you are brilliant and kind, and I am constantly impressed by you. ***Sanja***, you entered our office with a post-doc cool and calm at a time when both Emma and I were running around like headless chickens trying to finish our PhDs. Thank you for your steady presence. And to my ambitious teammate ***Makoto***, thank you for your kindness. I am so happy I got to share this experience with you. I was also incredibly lucky to find a true soul friend hidden in the department, the one and only lava-girl, ***Taylor***. You filled my days with laughter and silliness, and I cannot thank you enough for your friendship.

Beyond the academic world, my personal life has been a source of constant support and grounding. I have had the incredible luck of forming friendships that I treasure beyond words, and I will take this opportunity to put some of that love into print. To my ***Chari***, whom I have known since we were young girls and now as women, you are my steadiness and my constant reminder of true companionship. As I make the final push of this PhD, you are about to welcome your daughter into the world. It is one of my greatest honors to now know you in motherhood, and I am beyond excited for this new chapter in your life. To my pocket-friend and snail-girl, ***Yasmine***, who is off living her best life in Berlin, may you continue to grow, and may I always manage to keep up with you. ***Jonas***, a true spreader of joy and happiness, thank you for sharing your laughter and your beautiful children, and for being my best friend for so many years. To my ***sister*** and my newly born ***nephew***, you have my undivided love for eternity, thank you for giving me purpose. I aim to become the most outrageous auntie in the world.

And finally, to my MVH (most valuable human), ***Niclas***. My truest friend, who basically adopted me on my first awkward day at university nearly ten years ago. You are the steady love that everyone deserves, the unwavering support system that has carried me through the highs and lows of this PhD. You gave me rides to work on early weekend mornings and picked me up late at night. You comforted me when I was down and celebrated every small accomplishment. Most importantly, you reminded me of the joy of life beyond work. Having you as my friend is the greatest accomplishment of my life so far. Thank you for adopting me all those years ago, for being my number one supporter, and my greatest source of happiness. Long may we reign!

References

Amelia, T. S. M., Khalik, W. M. A. W. M., Ong, M. C., Shao, Y. T., Pan, H.-J., & Bhubalan, K. (2021). Marine microplastics as vectors of major ocean pollutants and its hazards to the marine ecosystem and humans. *Progress in Earth and Planetary Science*, *8*(1), 12. https://doi.org/10.1186/s40645-020-00405-4

Andersson, S., & Nygren, K. (2023). *Befolkningsprognos Uppsala kommun 2023–2050* (KSN-2023-00114).

Arias, A. H., Ronda, A. C., Oliva, A. L., & Marcovecchio, J. E. (2019). Evidence of Microplastic Ingestion by Fish from the Bahía Blanca Estuary in Argentina, South America. *Bulletin of Environmental Contamination and Toxicology*, *102*(6), 750–756. https://doi.org/10.1007/s00128-019-02604-2

Ashoori, N., Teixido, M., Spahr, S., LeFevre, G. H., Sedlak, D. L., & Luthy, R. G. (2019). Evaluation of pilot-scale biochar-amended woodchip bioreactors to remove nitrate, metals, and trace organic contaminants from urban stormwater runoff. *Water Research*, *154*, 1–11. https://doi.org/10.1016/j.watres.2019.01.040

Baldwin, A. K., Corsi, S. R., & Mason, S. A. (2016). Plastic debris in 29 Great Lakes tributaries: Relations to watershed attributes and hydrology. *Environmental Science & Technology*, *50*(19), 10377–10385.

Besley, A., Vijver, M. G., Behrens, P., & Bosker, T. (2017). A standardized method for sampling and extraction methods for quantifying microplastics in beach sand. *Marine Pollution Bulletin*, *114*(1), 77–83. https://doi.org/10.1016/j.marpolbul.2016.08.055

Björklund, K., Cousins, A. P., Strömvall, A.-M., & Malmqvist, P.-A. (2009). Phthalates and nonylphenols in urban runoff: Occurrence, distribution and area emission factors. *Science of the Total Environment*, *407*(16), 4665–4672.

Björklund, K., & Li, L. (2014). *Adsorption of organic pollutants in stormwater: Evaluation of four potential sorbents*. Proceedings of the 13th International Conference on Urban Drainage.

Björklund, K., & Li, L. (2015). Evaluation of low-cost materials for sorption of hydrophobic organic pollutants in stormwater. *Journal of Environmental Management*, *159*, 106–114. https://doi.org/10.1016/j.jenvman.2015.05.005

Brassard, P., Godbout, S., & Raghavan, V. (2016). Soil biochar amendment as a climate change mitigation tool: Key parameters and mechanisms involved. *Journal of Environmental Management*, *181*, 484–497. https://doi.org/10.1016/j.jenvman.2016.06.063

Brennecke, D., Duarte, B., Paiva, F., Caçador, I., & Canning-Clode, J. (2016). Microplastics as vector for heavy metal contamination from the marine environment. *Estuarine, Coastal and Shelf Science*, *178*, 189–195.

Cabernard, L., Roscher, L., Lorenz, C., Gerdts, G., & Primpke, S. (2018). Comparison of Raman and Fourier Transform Infrared Spectroscopy for the Quantification of Microplastics in the Aquatic Environment. *Environmental Science & Technology*, *52*(22), 13279–13288. https://doi.org/10.1021/acs.est.8b03438

Campanale, C., Massarelli, C., Savino, I., Locaputo, V., & Uricchio, V. F. (2020). A Detailed Review Study on Potential Effects of Microplastics and Additives of Concern on Human Health. *International Journal of Environmental Research and Public Health*, *17*(4). https://doi.org/10.3390/ijerph17041212

Chen, Y., Li, T., Hu, H., Ao, H., Xiong, X., Shi, H., & Wu, C. (2021). Transport and fate of microplastics in constructed wetlands: A microcosm study. *Journal of Hazardous Materials*, *415*, 125615. https://doi.org/10.1016/j.jhazmat.2021.125615

Chrysikopoulos, C. V., & Syngouna, V. I. (2014). Effect of Gravity on Colloid Transport through Water-Saturated Columns Packed with Glass Beads: Modeling and Experiments. *Environmental Science & Technology*, *48*(12), 6805–6813. https://doi.org/10.1021/es501295n

Cutillas-Barreiro, L., Ansias-Manso, L., Fernández-Calviño, D., Arias-Estévez, M., Nóvoa-Muñoz, J. C., Fernández-Sanjurjo, M. J., Álvarez-Rodríguez, E., & Núñez-Delgado, A. (2014). Pine bark as bio-adsorbent for Cd, Cu, Ni, Pb and Zn: Batch-type and stirred flow chamber experiments. *Journal of Environmental Management*, *144*, 258–264. https://doi.org/10.1016/j.jenvman.2014.06.008

Davis, A. P., Hunt, W. F., Traver, R. G., & Clar, M. (2009). Bioretention technology: Overview of current practice and future needs. *Journal of Environmental Engineering*, *135*(3), 109–117. https://doi.org/10.1061/(ASCE)0733-9372(2009)135:3(109)

Dhakal, K. P., & Chevalier, L. R. (2016). Urban Stormwater Governance: The Need for a Paradigm Shift. *Environmental Management*, *57*(5), 1112–1124. https://doi.org/10.1007/s00267-016-0667-5

Do, T., Park, Y., Lim, B., Kim, S., Chae, M.-Y., & Chun, C.-H. (2023). Effect of the first-flush phenomenon on the quantification of microplastics in rainwater. *Marine Pollution Bulletin*, *187*, 114559. https://doi.org/10.1016/j.marpolbul.2022.114559

Dris, R., Gasperi, J., Rocher, V., Saad, M., Renault, N., & Tassin, B. (2015). Microplastic contamination in an urban area: A case study in Greater Paris. *Environmental Chemistry*, *12*(5), 592–599.

Elhacham, E., Ben-Uri, L., Grozovski, J., Bar-On, Y. M., & Milo, R. (2020). Global human-made mass exceeds all living biomass. *Nature*, *588*(7838), 442–444. https://doi.org/10.1038/s41586-020-3010-5

Fan, G., Lin, R., Wei, Z., Xiao, Y., Shangguan, H., & Song, Y. (2022). Effects of low impact development on the stormwater runoff and pollution control. *Science of The Total Environment*, *805*, 150404. https://doi.org/10.1016/j.scitotenv.2021.150404

Frey, J., Schmitz, P., Dufreche, J., & Gohr Pinheiro, I. (1999). Particle deposition in porous media: Analysis of hydrodynamic and weak inertial effects. *Transport in Porous Media*, *37*(1), 25–54.

Fuerhacker, M., Haile, T. M., Monai, B., & Mentler, A. (2011). Performance of a filtration system equipped with filter media for parking lot runoff treatment. *Desalination*, *275*(1), 118–125. https://doi.org/10.1016/j.desal.2011.02.041

Gaggini, E. L., Polukarova, M., Bondelind, M., Rødland, E., Strömvall, A.-M., Andersson-Sköld, Y., & Sokolova, E. (2024). Assessment of fine and coarse tyre wear particles along a highway stormwater system and in receiving waters: Occurrence and transport. *Journal of Environmental Management*, *367*, 121989. https://doi.org/10.1016/j.jenvman.2024.121989
Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances*, *3*(7), e1700782. https://doi.org/10.1126/sciadv.1700782
Gilbreath, A., McKee, L., Shimabuku, I., Lin, D., Werbowski, Zhu, X., Grbic, J., & Rochman, C. (2019). Multiyear Water Quality Performance and Mass Accumulation of PCBs, Mercury, Methylmercury, Copper, and Microplastics in a Bioretention Rain Garden. *Journal of Sustainable Water in the Built Environment*, *5*(4), 04019004. https://doi.org/10.1061/JSWBAY.0000883
Goßmann, I., Süßmuth, R., & Scholz-Böttcher, B. M. (2022). Plastic in the air?! - Spider webs as spatial and temporal mirror for microplastics including tire wear particles in urban air. *Science of The Total Environment*, *832*, 155008. https://doi.org/10.1016/j.scitotenv.2022.155008
Hahladakis, J. N., Velis, C. A., Weber, R., Iacovidou, E., & Purnell, P. (2018). An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. *Journal of Hazardous Materials*, *344*, 179–199. https://doi.org/10.1016/j.jhazmat.2017.10.014
Hanif, M. A., Ibrahim, N., Dahalan, F. A., Md. Ali, U. F., Hasan, M., Azhari, A. W., & Jalil, A. A. (2023). Microplastics in facial cleanser: Extraction, identification, potential toxicity, and continuous-flow removal using agricultural waste–based biochar. *Environmental Science and Pollution Research*, *30*(21), 60106–60120. https://doi.org/10.1007/s11356-023-26741-8
Hartmann, N. B., Hüffer, T., Thompson, R. C., Hassellöv, M., Verschoor, A., Daugaard, A. E., Rist, S., Karlsson, T., Brennholt, N., Cole, M., Herrling, M. P., Hess, M. C., Ivleva, N. P., Lusher, A. L., & Wagner, M. (2019). Are We Speaking the Same Language? Recommendations for a Definition and Categorization Framework for Plastic Debris. *Environmental Science & Technology*, *53*(3), 1039–1047. https://doi.org/10.1021/acs.est.8b05297
Horton, A. A., Walton, A., Spurgeon, D. J., Lahive, E., & Svendsen, C. (2017). Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. *Science of The Total Environment*, *586*, 127–141. https://doi.org/10.1016/j.scitotenv.2017.01.190
Hsieh, L., He, L., Zhang, M., Lv, W., Yang, K., & Tong, M. (2022). Addition of biochar as thin preamble layer into sand filtration columns could improve the microplastics removal from water. *Water Research*, *221*, 118783. https://doi.org/10.1016/j.watres.2022.118783
Jamaludin, N., Rashid, S. A., & Tan, T. (2019). Chapter 5—Natural Biomass as Carbon Sources for the Synthesis of Photoluminescent Carbon Dots. In S. A. Rashid, R. N. I. Raja Othman, & M. Z. Hussein (Eds.), *Synthesis, Technology and Applications of Carbon Nanomaterials* (pp. 109–134). Elsevier. https://doi.org/10.1016/B978-0-12-815757-2.00005-X
Järlskog, I., Strömvall, A.-M., Magnusson, K., Gustafsson, M., Polukarova, M., Galfi, H., Aronsson, M., & Andersson-Sköld, Y. (2020). Occurrence of tire and bitumen wear microplastics on urban streets and in sweepsand and washwater. *Science of The Total Environment*, *729*, 138950. https://doi.org/10.1016/j.scitotenv.2020.138950

Johansson, G., Fedje, K. K., Modin, O., Haeger-Eugensson, M., Uhl, W., Andersson-Sköld, Y., & Strömvall, A.-M. (2024). Removal and Release of Microplastics and Other Environmental Pollutants during the Start-up of Bioretention Filters Treating Stormwater. *Journal of Hazardous Materials*, 133532. https://doi.org/10.1016/j.jhazmat.2024.133532

Jönsson, R. (2016). Microplastics in Stormwater and Sewage − Removal in Stormwater Ponds and Constructed Wetlands [Student thesis]. In *UPTEC W: Vol. Independent thesis Advanced level (professional degree)*. DiVA. http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-308455

Kooi, M., Besseling, E., Kroeze, C., van Wezel, A. P., & Koelmans, A. A. (2018). Modeling the Fate and Transport of Plastic Debris in Freshwaters: Review and Guidance. In M. Wagner & S. Lambert (Eds.), *Freshwater Microplastics: Emerging Environmental Contaminants?* (pp. 125–152). Springer International Publishing. https://doi.org/10.1007/978-3-319-61615-5_7

Kuoppamäki, K., Pflugmacher Lima, S., Scopetani, C., & Setälä, H. (2021). The ability of selected filter materials in removing nutrients, metals, and microplastics from stormwater in biofilter structures. *Journal of Environmental Quality*, *50*(2), 465–475. https://doi.org/10.1002/jeq2.20201

Lange, K., Furén, R., Österlund, H., Winston, R., Tirpak, R. A., Nordqvist, K., Smith, J., Dorsey, J., Viklander, M., & Blecken, G.-T. (2023). Abundance, distribution, and composition of microplastics in the filter media of nine aged stormwater bioretention systems. *Chemosphere*, *320*, 138103. https://doi.org/10.1016/j.chemosphere.2023.138103

Lange, K., Magnusson, K., Viklander, M., & Blecken, G.-T. (2021a). Removal of rubber, bitumen and other microplastic particles from stormwater by a gross pollutant trap—Bioretention treatment train. *Water Research*, *202*, 117457. https://doi.org/10.1016/j.watres.2021.117457

Lange, K., Magnusson, K., Viklander, M., & Blecken, G.-T. (2021b). Removal of rubber, bitumen and other microplastic particles from stormwater by a gross pollutant trap—Bioretention treatment train. *Water Research*, *202*, 117457. https://doi.org/10.1016/j.watres.2021.117457

Lange, K., Österlund, H., Viklander, M., & Blecken, G.-T. (2022). Occurrence and concentration of 20–100 μm sized microplastic in highway runoff and its removal in a gross pollutant trap – Bioretention and sand filter stormwater treatment train. *Science of The Total Environment*, *809*, 151151. https://doi.org/10.1016/j.scitotenv.2021.151151

Li, X., Chen, L., Ji, Y., Li, M., Dong, B., Qian, G., Zhou, J., & Dai, X. (2020). Effects of chemical pretreatments on microplastic extraction in sewage sludge and their physicochemical characteristics. *Water Research*, *171*, 115379. https://doi.org/10.1016/j.watres.2019.115379

Liu, F., Nord, N. B., Bester, K., & Vollertsen, J. (2020). Microplastics Removal from Treated Wastewater by a Biofilter. *Water*, *12*(4). https://doi.org/10.3390/w12041085

Liu, F., Olesen, K. B., Borregaard, A. R., & Vollertsen, J. (2019). Microplastics in urban and highway stormwater retention ponds. *Science of The Total Environment*, *671*, 992–1000. https://doi.org/10.1016/j.scitotenv.2019.03.416

Liu, S., Shi, J., Wang, J., Dai, Y., Li, H., Li, J., Liu, X., Chen, X., Wang, Z., & Zhang, P. (2021). Interactions Between Microplastics and Heavy Metals in Aquatic Environments: A Review. *Frontiers in Microbiology*, *12*. https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2021.652520

Logemann, J., Oveland, E., Bjorøy, Ø., peters, wibke, Cojocariu, C., & Kögel, T. (2018). *Pyrolysis-GC-Orbitrap MS - a powerful analytical tool for identification and quantification of microplastics in a biological matrix*.

Lusher, A. L., Bråte, I. L. N., Munno, K., Hurley, R. R., & Welden, N. A. (2020). Is It or Isn't It: The Importance of Visual Classification in Microplastic Characterization. *Applied Spectroscopy*, *74*(9), 1139–1153. https://doi.org/10.1177/0003702820930733

Markiewicz, A., Björklund, K., Eriksson, E., Kalmykova, Y., Strömvall, A.-M., & Siopi, A. (2017). Emissions of organic pollutants from traffic and roads: Priority pollutants selection and substance flow analysis. *Science of the Total Environment*, *580*, 1162–1174.

Masura, J., Baker, J. E., 1959-, Foster, G. D. (Gregory D., Arthur, C., & Herring, C. (2015). *Laboratory methods for the analysis of microplastics in the marine environment: Recommendations for quantifying synthetic particles in waters and sediments* (noaa:10296). https://repository.library.noaa.gov/view/noaa/10296

Mohanty, S. K., & Boehm, A. B. (2014). Escherichia coli Removal in Biochar-Augmented Biofilter: Effect of Infiltration Rate, Initial Bacterial Concentration, Biochar Particle Size, and Presence of Compost. *Environmental Science & Technology*, *48*(19), 11535–11542. https://doi.org/10.1021/es5033162

Monira, S., Bhuiyan, M. A., Haque, N., Shah, K., Roychand, R., Hai, F. I., & Pramanik, B. K. (2021). Understanding the fate and control of road dust-associated microplastics in stormwater. *Process Safety and Environmental Protection*, *152*, 47–57. https://doi.org/10.1016/j.psep.2021.05.033

Müller, A., Österlund, H., Marsalek, J., & Viklander, M. (2020). The pollution conveyed by urban runoff: A review of sources. *Science of The Total Environment*, *709*, 136125. https://doi.org/10.1016/j.scitotenv.2019.136125

Nelms, S. E., Galloway, T. S., Godley, B. J., Jarvis, D. S., & Lindeque, P. K. (2018). Investigating microplastic trophic transfer in marine top predators. *Environmental Pollution*, *238*, 999–1007. https://doi.org/10.1016/j.envpol.2018.02.016

Olesen, K. B., Stephansen, D. A., van Alst, N., & Vollertsen, J. (2019). Microplastics in a Stormwater Pond. *Water*, *11*(7). https://doi.org/10.3390/w11071466

Österlund, H., Blecken, G., Lange, K., Marsalek, J., Gopinath, K., & Viklander, M. (2023). Microplastics in urban catchments: Review of sources, pathways, and entry into stormwater. *Science of The Total Environment*, *858*, 159781. https://doi.org/10.1016/j.scitotenv.2022.159781

Österlund, H., & Fältström, E. (2023). *Sources, sinks and flows of microplastics in the urban environment* (Project Report Report 7104). https://www.naturvardsverket.se/49ec4a/globalassets/media/publikationer-pdf/7100/978-91-620-7104-2.pdf

Pankkonen, P. (2020). *Urban stormwater microplastics   Characteristics and removal using a developed filtration system*. Aalto University School of Engineering.

Perera, K., Ziajahromi, S., Bengtson Nash, S., Manage, P. M., & Leusch, F. D. (2022). Airborne microplastics in indoor and outdoor environments of a developing country in South Asia: Abundance, distribution, morphology, and possible sources. *Environmental Science & Technology*, *56*(23), 16676–16685.

Perera, K., Ziajahromi, S., Nash, S. B., & Leusch, F. D. L. (2023). Microplastics in Australian indoor air: Abundance, characteristics, and implications for human exposure. *Science of The Total Environment*, *889*, 164292. https://doi.org/10.1016/j.scitotenv.2023.164292

PlasticsEurope. (2020).

PlasticsEurope. (2023). Plastics – the fast Facts 2023. *Plastics Europe*. https://plasticseurope.org/knowledge-hub/plastics-the-fast-facts-2023/

Primpke, S., Cross, R. K., Mintenig, S. M., Simon, M., Vianello, A., Gerdts, G., & Vollertsen, J. (2020). Toward the Systematic Identification of Microplastics in the Environment: Evaluation of a New Independent Software Tool (siMPle) for Spectroscopic Analysis. *Applied Spectroscopy*, *74*(9), 1127–1138. https://doi.org/10.1177/0003702820917760

Primpke, S., Lorenz, C., Rascher-Friesenhausen, R., & Gerdts, G. (2017). An automated approach for microplastics analysis using focal plane array (FPA) FTIR microscopy and image analysis. *Anal. Methods*, *9*(9), 1499–1511. https://doi.org/10.1039/C6AY02476A

Primpke, S., Wirth, M., Lorenz, C., & Gerdts, G. (2018). Reference database design for the automated analysis of microplastic samples based on Fourier transform infrared (FTIR) spectroscopy. *Analytical and Bioanalytical Chemistry*, *410*(21), 5131–5141. https://doi.org/10.1007/s00216-018-1156-x

Ribeiro, F., O'Brien, J. W., Galloway, T., & Thomas, K. V. (2019). Accumulation and fate of nano- and micro-plastics and associated contaminants in organisms. *TrAC Trends in Analytical Chemistry*, *111*, 139–147. https://doi.org/10.1016/j.trac.2018.12.010

Rowell, R. M., Pettersen, R., Han, J. S., Rowell, J. S., & Tshabalala, M. A. (2005). Cell wall chemistry. *Handbook of Wood Chemistry and Wood Composites*, *2*, 33–72.

Rummel, C. D., Jahnke, A., Gorokhova, E., Kühnel, D., & Schmitt-Jansen, M. (2017). Impacts of Biofilm Formation on the Fate and Potential Effects of Microplastic in the Aquatic Environment. *Environmental Science & Technology Letters*, *4*(7), 258–267. https://doi.org/10.1021/acs.estlett.7b00164

Shafi, M., Lodh, A., Khajuria, M., Ranjan, V. P., Gani, K. M., Chowdhury, S., & Goel, S. (2024). Are we underestimating stormwater? Stormwater as a significant source of microplastics in surface waters. *Journal of Hazardous Materials*, *465*, 133445. https://doi.org/10.1016/j.jhazmat.2024.133445

Shah, A. A., Hasan, F., Hameed, A., & Ahmed, S. (2008). Biological degradation of plastics: A comprehensive review. *Biotechnology Advances*, *26*(3), 246–265.

Siegfried, M., Koelmans, A. A., Besseling, E., & Kroeze, C. (2017). Export of microplastics from land to sea. A modelling approach. *Water Research*, *127*, 249–257. https://doi.org/10.1016/j.watres.2017.10.011

Simon, M., van Alst, N., & Vollertsen, J. (2018). Quantification of microplastic mass and removal rates at wastewater treatment plants applying Focal Plane Array (FPA)-based Fourier Transform Infrared (FT-IR) imaging. *Water Research*, *142*, 1–9. https://doi.org/10.1016/j.watres.2018.05.019

SiMPle. (2022). *About*. Simple-Plastics.Eu. https://simple-plastics.eu/about.html

Smyth, K., Drake, J., Li, Y., Rochman, C., Van Seters, T., & Passeport, E. (2021). Bioretention cells remove microplastics from urban stormwater. *Water Research*, *191*, 116785. https://doi.org/10.1016/j.watres.2020.116785

Song, Y. K., Hong, S. H., Jang, M., Han, G. M., Rani, M., Lee, J., & Shim, W. J. (2015). A comparison of microscopic and spectroscopic identification methods for analysis of microplastics in environmental samples. *Marine Pollution Bulletin*, *93*(1), 202–209. https://doi.org/10.1016/j.marpolbul.2015.01.015

Subair, A., Krishnamoorthy Lakshmi, P., Chellappan, S., & Chinghakham, C. (2024). Removal of polystyrene microplastics using biochar-based continuous flow fixed-bed column. *Environmental Science and Pollution Research*, *31*(9), 13753–13765. https://doi.org/10.1007/s11356-024-32088-5
Sun, X., Jia, Q., Ye, J., Zhu, Y., Song, Z., Guo, Y., & Chen, H. (2023). Real-time variabilities in microplastic abundance and characteristics of urban surface runoff and sewer overflow in wet weather as impacted by land use and storm factors. *Science of The Total Environment*, *859*, 160148. https://doi.org/10.1016/j.scitotenv.2022.160148
Szewc, K., Graca, B., & Dołęga, A. (2021). Atmospheric deposition of microplastics in the coastal zone: Characteristics and relationship with meteorological factors. *Science of The Total Environment*, *761*, 143272. https://doi.org/10.1016/j.scitotenv.2020.143272
Thompson, R. C., Olsen, Y., Mitchell, R. P., Davis, A., Rowland, S. J., John, A. W. G., McGonigle, D., & Russell, A. E. (2004). Lost at Sea: Where Is All the Plastic? *Science*, *304*(5672), 838–838. https://doi.org/10.1126/science.1094559
Treilles, R., Gasperi, J., Gallard, A., Saad, M., Dris, R., Partibane, C., Breton, J., & Tassin, B. (2021). Microplastics and microfibers in urban runoff from a suburban catchment of Greater Paris. *Environmental Pollution*, *287*, 117352. https://doi.org/10.1016/j.envpol.2021.117352
Ulrich, B. A., Vignola, M., Edgehouse, K., Werner, D., & Higgins, C. P. (2017). Organic Carbon Amendments for Enhanced Biological Attenuation of Trace Organic Contaminants in Biochar-Amended Stormwater Biofilters. *Environmental Science & Technology*, *51*(16), 9184–9193. https://doi.org/10.1021/acs.est.7b01164
Vivekanand, A. C., Mohapatra, S., & Tyagi, V. K. (2021). Microplastics in aquatic environment: Challenges and perspectives. *Chemosphere*, *282*, 131151.
Vogelsang, C., Lusher, A. L., Dadkhah, M. E., Sundvor, I., Umar, M., Ranneklev, S. B., Eidsvoll, D. P., & Meland, S. (2019). *Microplastics in road dust – characteristics, pathways and measures*. https://api.semanticscholar.org/CorpusID:134350105
Wang, Q., Hernández-Crespo, C., Santoni, M., Van Hulle, S., & Rousseau, D. P. L. (2020a). Horizontal subsurface flow constructed wetlands as tertiary treatment: Can they be an efficient barrier for microplastics pollution? *Science of The Total Environment*, *721*, 137785. https://doi.org/10.1016/j.scitotenv.2020.137785
Wang, Z., Sedighi, M., & Lea-Langton, A. (2020b). Filtration of microplastic spheres by biochar: Removal efficiency and immobilisation mechanisms. *Water Research*, *184*, 116165. https://doi.org/10.1016/j.watres.2020.116165
Wei, L., Yue, Q., Chen, G., & Wang, J. (2023). Microplastics in rainwater/stormwater environments: Influencing factors, sources, transport, fate, and removal techniques. *TrAC Trends in Analytical Chemistry*, *165*, 117147. https://doi.org/10.1016/j.trac.2023.117147
Werbowski, L. M., Gilbreath, A. N., Munno, K., Zhu, X., Grbic, J., Wu, T., Sutton, R., Sedlak, M. D., Deshpande, A. D., & Rochman, C. M. (2021). Urban Stormwater Runoff: A Major Pathway for Anthropogenic Particles, Black Rubbery Fragments, and Other Types of Microplastics to Urban Receiving Waters. *ACS ES&T Water*, *1*(6), 1420–1428. https://doi.org/10.1021/acsestwater.1c00017

Zarezadeh, V., Lung, T., Dorman, T., Shipley, H. J., & Giacomoni, M. (2018). Assessing the performance of sand filter basins in treating urban stormwater runoff. *Environmental Monitoring and Assessment*, *190*(12). https://doi.org/10.1007/s10661-018-7069-5
Ziajahromi, S., Drapper, D., Hornbuckle, A., Rintoul, L., & Leusch, F. D. L. (2020). Microplastic pollution in a stormwater floating treatment wetland: Detection of tyre particles in sediment. *Science of The Total Environment*, *713*, 136356. https://doi.org/10.1016/j.scitotenv.2019.136356

Acta Universitatis Upsaliensis

Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 2533

Editor: The Dean of the Faculty of Science and Technology

A doctoral dissertation from the Faculty of Science and Technology, Uppsala University, is usually a summary of a number of papers. A few copies of the complete dissertation are kept at major Swedish research libraries, while the summary alone is distributed internationally through the series Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology. (Prior to January, 2005, the series was published under the title "Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology".)

ACTA UNIVERSITATIS
UPSALIENSIS
2025

Distribution: publications.uu.se
urn:nbn:se:uu:diva-554039