Reviews of Environmental Contamination and Toxicology (2025) 263:5
https://doi.org/10.1007/s44169-025-00078-4

REVIEW

Global Occurrence and Environmental Fate of Microplastics in Stormwater Runoff: Unlock the In-depth Knowledge on Nature-Based Removal Strategies

Van-Hiep Hoang[1] · Minh-Ky Nguyen[2] · Tuan-Dung Hoang[3,4] · Hoang-Lam Nguyen[5] · Chitsan Lin[6] · Balal Yousaf[7] · Minh Cuong Ha[8] · Vu Khac Hoang Bui[9,10] · Minh-Thuan Pham[11,12] · S. Woong Chang[13] · D. Duc Nguyen[13,14]

Received: 28 May 2024 / Accepted: 11 January 2025

Abstract

Microplastics (MPs), defined as plastic particles smaller than 5 mm, originate from the degradation of larger plastic items or manufactured products, such as microbeads. Stormwater runoff is increasingly recognized as a critical pathway for introducing MPs into marine environments, thereby threatening both ecosystems and human health. Despite growing concerns over MPs as emerging contaminants, a significant knowledge gap remains regarding their global distribution and the associated challenges to human health. This highlights the need for comprehensive research into the factors influencing MP contamination in stormwater runoff. To collect data, the search was restricted to academic articles published between 2020 and 2024. After careful screening, 45 reports were selected and included in the current study. The sizes and global levels of MPs in stormwater runoff vary widely, with dominant particles being less than 1000 µm and concentrations ranging from as low as 1.2–3 particles/L to as high as 11,932 ± 151 to 18,966 ± 191 particles/L. Common MPs identified in stormwater include fragments, fibers, foams, films, rubbery particles, and spheres. The research findings underscore stormwater runoff as a significant pathway for transporting MPs within urban settings. Therefore, it is essential to prioritize treatment strategies specifically

✉ Minh-Ky Nguyen
nmky@hcmuaf.edu.vn

✉ D. Duc Nguyen
nguyensyduc@gmail.com

1 Hanoi - School of Interdisciplinary Sciences and Arts, Vietnam National University, 144 Xuan Thuy Street, Cau Giay District, Hanoi 100000, Vietnam

2 Faculty of Environment and Natural Resources, Nong Lam University, Hamlet 22, Linh Trung Ward, Thu Duc City, Ho Chi Minh City 700000, Vietnam

3 School of Chemistry and Life Science, Hanoi University of Science and Technology, No. 1 Dai Co Viet, Hai Ba Trung, Hanoi 100000, Vietnam

4 Vietnam National University, VNU Town, Hoa Lac, Thach That District, Hanoi 155500, Vietnam

5 Department of Civil Engineering, McGill University, Montreal, Canada

6 Department of Marine Environmental Engineering, National Kaohsiung University of Science and Technology, Kaohsiung 81157, Taiwan

7 Department of Technologies and Installations for Waste Management, Faculty of Energy and Environmental Engineering, Silesian University of Technology, Konarskiego 18, 44-100, Gliwice, Poland

8 School of Aerospace Engineering (SAE), University of Engineering and Technology (UET), Vietnam National University (VNU), Hanoi 100000, Vietnam

9 Laboratory for Advanced Nanomaterials and Sustainable Energy Technologies, Institute for Computational Science and Artificial Intelligence, Van Lang University, Ho Chi Minh City, Vietnam

10 Faculty of Applied Technology, School of Technology, Van Lang University, Ho Chi Minh City, Vietnam

11 Center for Environmental Toxin and Emerging-Contaminant Research, Cheng Shiu University, Kaohsiung 83347, Taiwan

12 Institute of Environmental Toxin and Emerging-Contaminant, Cheng Shiu University, Kaohsiung 833301, Taiwan

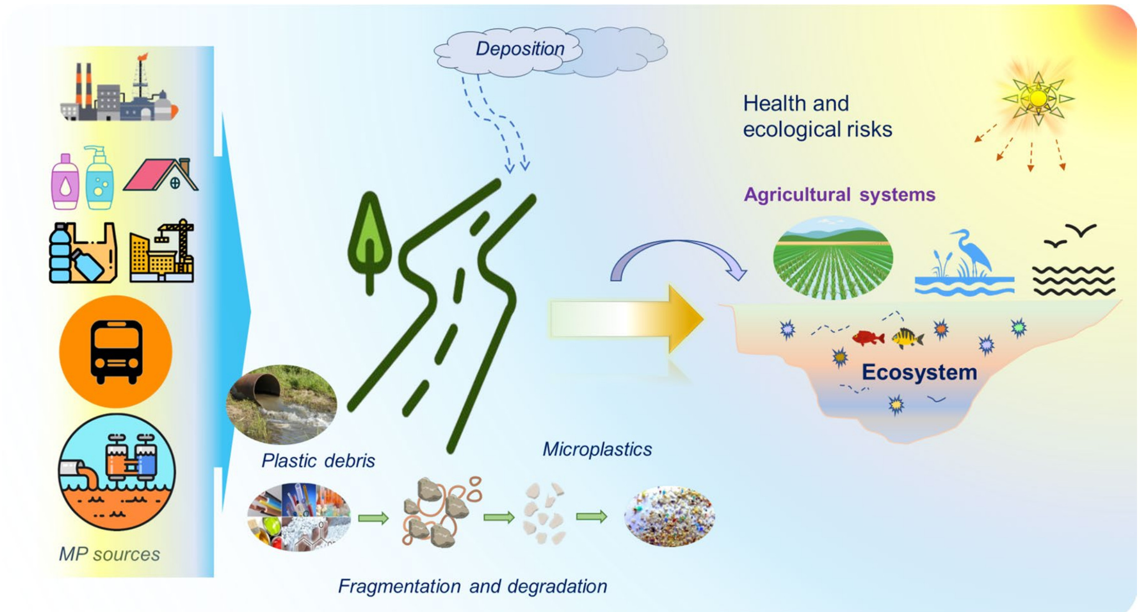
13 Department of Civil & Energy System Engineering, Kyonggi University, Suwon 16227, South Korea

14 School of Engineering & Technology, Duy Tan University, Da Nang, Vietnam

Published online: 28 January 2025

designed to remove MPs effectively. This necessitates adopting nature-based solutions like bioretention cells, rain gardens, sustainable urban drainage systems (SUDS), and constructed wetlands. Such strategies harness the inherent capabilities of natural ecosystems to efficiently filter and capture MPs, thereby significantly reducing pollution from stormwater runoff.

Graphical Abstract



Introduction

Plastics have pervaded human society owing to their versatility and affordability. However, the rising consumption of plastics in recent years has underscored the profound effects that plastic fragments and microplastics (MPs) can exert on freshwater and marine ecosystems (Horton & Barnes 2020; Le et al. 2024a; Nguyen et al. 2024c). Approximately, 60% of the plastics produced globally have already been accumulated in landfills and/or environmental matrices (Geyer et al. 2017). Once released, plastics undergo many mechanical, physicochemical, and biologic processes. These include photodegradation, mechanical abrasion, thermal oxidation, chemical oxidation, hydrolysis, and biodegradation. These processes lead to further aging and fragmentation, ultimately generating secondary MPs (Hanun et al. 2021). Beyond the initial degradation of plastic products into smaller debris, secondary MPs emerge as the primary contributors to MP-associated contamination. With time, these MPs continue to degrade into even smaller particles, categorized as nanoplastics (less than 100 nm in size). Thus, the escalating usage of plastics raises a growing concern due to their detrimental environmental impacts.

MPs, defined as polymer debris/particles less than size based 5 mm, have been identified in various environmental matrices, including air, soil, surface/groundwater, drinking supply water, and human as well as animal feces (Fahrenfeld et al. 2019; Nguyen et al. 2022b), and are of significant global concern as an emerging environmental contaminant (Nguyen et al. 2024c; Winiarska et al. 2024). Research indicates that MPs are widespread in the environment, with negative consequences observed for terrestrial and aquatic organisms (Foley et al. 2018; Le et al. 2024b). The ingestion of MPs by marine living organisms can result in various adverse effects, such as energy depletion, growth inhibition, disruption of the immune system, and, in severe cases, mortality. Consequently, the escalating ecological threats MPs pose are a growing concern. Stormwater runoff is a significant route for transporting MPs from land-related sources to ecological compartments (Kabir et al. 2024). Nevertheless, our understanding of MPs transferring aquatic ecosystems through non-point sources, particularly regarding the temporal dynamics of MP discharge via stormwater runoff remains limited (Cho et al. 2023).

MPs have been demonstrated to be transported via stormwater runoff in various environments, including from urban to rural, suburban, remote zones, and even agricultural areas (de Jesus Piñon-Colin et al. 2020; Monira et al. 2021; Wang et al. 2022). For instance, stormwater runoff, exhibiting MP levels varying from 0.4 particles/L to 191 particles/L, has been known as an essential pathway for MP entry into aquatic ecosystems (de Jesus Piñon-Colin et al. 2020; Liu et al. 2019a; Stang et al. 2022). Stormwater runoff flows play a pivotal role in facilitating the movement of land-based MPs to surface water bodies. Since the escalating concern regarding MPs related to stormwater runoff, the focus has predominantly been on urban or industrial areas (Monira et al. 2022; Niu et al. 2024; Xue et al. 2023). Most importantly, in recent years, the utilization of single-use plastic (SUP)-based medical equipment, including disposable gloves and face masks, has surged dramatically due to the COVID-19 pandemic (Van-Giang et al. 2024). This surge has resulted in a notable increase in MP pollution entering aquatic environments from stormwater runoff and adverse risks to urban or industrial areas and agricultural ecosystems (Devereux et al. 2023; Malli et al. 2023; Tiwari et al. 2023).

Concerns regarding MP pollution from stormwater runoff have recently escalated rapidly (de Jesus Piñon-Colin et al. 2020; Niu et al. 2024; Parameswarappa Jayalakshmamma et al. 2023). Despite the proliferating growth in concern about MPs, there have been a scarcity of investigations specifically focusing on MP contamination in stormwater associated with human health and ecological concerns. For instance, stormwater runoff plays a crucial role in transporting MPs originating from urban environments (Parameswarappa Jayalakshmamma et al. 2023). Stormwater runoff, recognized as a non-point source of MPs, should receive much attention in terms of investigating the fate and environmental transport of MPs in runoff and its impact on ecological systems. Considering the significant influences of MPs on aquatic ecosystems and adverse challenges, their treatment in stormwater environments is paramount. Additionally, nature-based techniques, such as bioretention systems (also known as rain gardens—engineered filter media and vegetation and are part of the broader category of sustainable urban drainage systems (SUDS)) and constructed wetlands, show promise for removing MPs and deserve further investigation (García-Haba et al. 2023; Wei et al. 2023). The main points of this review were (1) to determine the global challenge and environmental fate of MPs in stormwater runoff and (2) to unlock in-depth knowledge on nature-based MP removal strategies. This study aims to fill this critical gap, giving new insights into the environmental pathways and risks associated with MPs in stormwater runoff. By addressing these knowledge gaps, the challenges posed by MPs in stormwater environments can be tackled, and practical solutions to combat their pollution can be proposed.

Methodology

To collect data, the search criteria were restricted to journal articles, books, and academic reports published in English between 2020 and January 2024. Based on "<Title>, <Abstract>, and <Keywords>" in databases, such as "Web of Science," "Scopus," and "Google Scholar," search criteria for literature using the query TS = ("microplastic," OR "MP," OR "micron-sized plastic," OR "micro-plastic," OR "plastic debris," OR "plastic," OR "polyethylene," OR "PE," OR "polypropylene," OR "PP," OR "polyester," OR "PES," OR "polyamide," OR "PA," OR "polystyrene," OR "PS," OR "polyethylene terephthalate," OR "PET," OR "polyurethane," OR "PU," OR "polyacrylonitrile," OR "PAN," OR "polyvinyl chloride," OR "PVC,") AND TS = ("source," OR "occurrence," OR "distribution," OR "fate," OR "behavior," OR "transport,") AND TS = ("stormwater," OR "runoff," OR "aquatic," OR "ecological concern,") AND TS = ("nature-based solution," OR "NbS," OR " bioretention cell," OR "rain garden," OR "constructed wetland", OR "CW," OR "sustainable urban drainage system," OR "SUDS,"). Also, a thorough review of the important references in the selected records and pertinent reports was performed to find additional relevant articles. Initially, 487 results were identified that met the search criteria. After eliminating 115 duplicate reports, the titles and abstracts of 372 reports were reviewed. After refining the search, 45 bibliographies were selected and used in the current study.

Sources, Environmental Occurrence, and Fate of Microplastics in Stormwater Runoff

Contamination Sources

The rise of urbanization and our activities have led to a widespread global environmental issue, such as the pollution of MPs via stormwater runoff (Fig. 1). Vast quantities of MPs are carried from urban areas via surface runoff into various natural ecosystems, e.g., lakes, rivers, reservoirs, ponds, estuaries, and oceans (Wang et al. 2022). Through a straightforward apportionment approach, researchers identified approximately 85% of the MP sources in industrial, transportation, and residential sites (Xue et al. 2023). Primary contributors to MP pollution in stormwater runoff include tire particles, atmospheric deposition, artificial turf, industrial discharge, and litter (Österlund et al. 2023). Road dust, a significant source of urban MPs, mainly consists of tire wear particles from vehicle friction (Campanale et al. 2022; Van-Giang et al. 2023). Since the impact of COVID-19, face masks have emerged as a significant contributor to MP pollution. Rainwater and stormwater systems are crucial in transporting MPs from diverse sources like surface runoff, drainage systems, and atmospheric deposition (Werbowski et al. 2021). Rainfall is the most direct and significant agent for generating surface runoff, and it has also been proposed

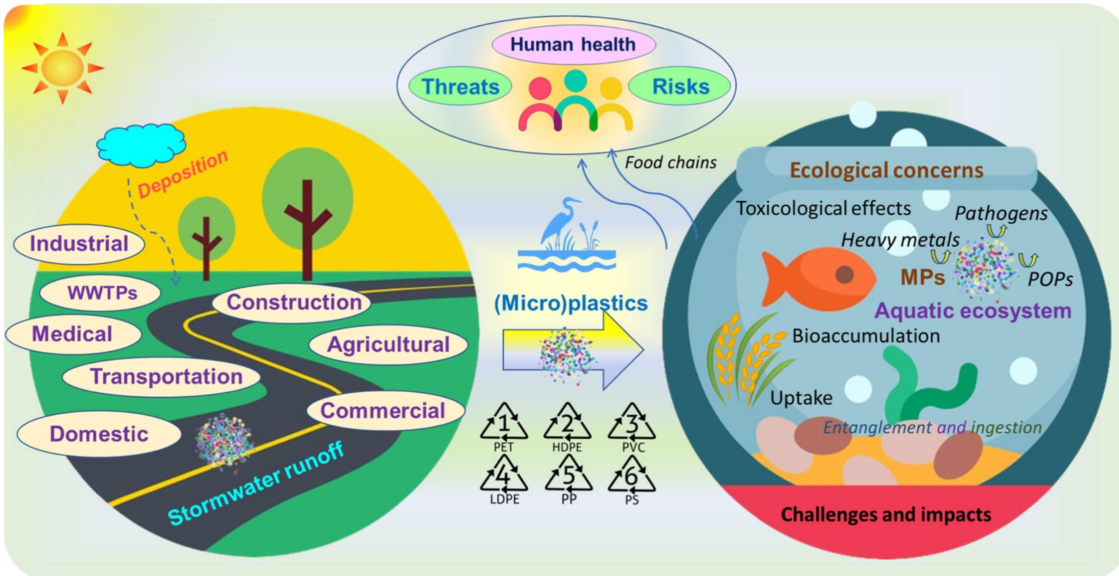


Fig. 1 Sources, fate, and ecological concerns of microplastics in stormwater runoff

to enhance atmospheric MP deposition (Van-Giang et al. 2023; Zhang et al. 2023). MPs suspended in the atmosphere are settled into surface runoff flows throughout rainfall events.

MP pollution can also arise from various other sources, including agricultural and coastal, as well as domestic/daily activities (Hoang et al. 2024; Wang et al. 2022). This MP pollution is primarily caused by directly releasing particles and/or pellets into the environment. Such releases occur through abrasives in products such as shaving cream and toothpaste and the laundering of synthetic textile fabrics and other goods. Secondary MP pollution can occur due to the decomposition-fragmentation of larger plastic materials, e.g., plastic bottles, plastic bags, fishing nets, and other waste plastics. Samples conducted in New Jersey, US revealed that MP concentrations in stormwater runoff are considerably higher than those released in wastewater effluents or dispersed in the atmospheric environment (Bailey et al. 2021).

In metropolitan regions, a substantial volume of plastic waste is inadequately managed. It ends up as litter, posing a high potential for degradation and ultimately becoming a significant source of MPs in stormwater runoff (Shruti et al. 2021). Additional sources of MPs in stormwater runoff encompass leachate from landfills, construction sites, and fragments from polymer-based paints and coatings (Grbić et al. 2020; Shruti et al. 2021). Also, the composition of MPs is expected to vary depending on land use. MPs can indeed be influenced by various urban land use types (Xue et al. 2023). The varying land uses within urban catchments are associated with distinct sources of MP contamination. The geographic location and land use patterns of a study area are critical in determining MP abundance. Polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), and polystyrene (PS) are among the most abundant and frequent polymers in stormwater runoff. This spatial variability of MPs significantly contributes to their emergence in stormwater runoff (Fang et al. 2021). Several factors contribute to significant variations in the characteristics and abundance of MPs in stormwater runoff, including meteorological conditions (such as rainfall intensity and antecedent dry days) and the frequency of urban cleansing activities (Wei et al. 2023). Hydrological conditions significantly impact the abundance of MPs (Sewwandi et al. 2024). Analyzing the characteristics and abundance of MPs in stormwater runoff offers valuable insights into contamination sources and their impacts on catchment environments. This waste can gradually decompose into smaller MP pieces through processes, such as mechanical abrasion, exposure to ultraviolet (UV) radiation, and biodegradation (Song et al. 2017; Van-Re et al. 2023). Further examination of their fate and transport is needed. Investigate how different processes (mechanical abrasion, UV exposure, biodegradation) contribute to the breakdown of plastics into MPs. Research should focus on how these processes vary under different environmental conditions and over time. Also, long-term studies should be conducted to understand the temporal dynamics of MP pollution, including seasonal variations and the cumulative effects of MPs on natural ecosystems and human health.

Environmental Occurrence

Numerous studies have examined the presence and attributes of MPs in stormwater runoff (Table 1). It indicates that urban stormwater often contains high levels of microparticles, encompassing both plastic and natural fibers. In Korea, MPs have been recognized in stormwater runoff from residential and industrial areas, with concentrations varying from 68 particles/L to 568 particles/L in industrial areas and from 54 particles/L to 639 particles/L in residential areas (Cho et al. 2023). Fragments were the most common MP shape, typically measuring between 20–100 µm and 100–200 µm. The particle count ranged from 0.3 particles/L to 17.3 particles/L reported in the stormwater runoff from a medium-scaled city in Thailand (Xue et al. 2023). The reported content was 8580 particles/L, ranging from 20 to 100 µm, collected at the inlet of the stormwater treatment plant in Sweden (Lange et al. 2022). The distribution of MPs exhibited spatial heterogeneity, as evidenced by significant differences in concentrations observed across various countries or regions. Extremely high MP counts (5–100 µm) were reported in Italy with 11,932 ± 151–18,966 ± 191 particles/L (Rosso et al. 2022). The high mean MP concentration observed in stormwater samples can be attributed to road dust and urban plastic waste, which are key sources of MPs (Sewwandi et al. 2024). According to Schernewski et al. (2021), a significant portion, approximately 62%, of the MPs found in the Baltic Sea can be traced back to stormwater runoff.

As mentioned, stormwater runoff is determined as a primary route for transporting land-based MPs into aquatic ecosystems (Cho et al. 2023). For example, the distribution, abundance, and detailed characteristics of MPs in stormwater runoff across different land use types can provide significant information. Xue et al. (2023) illustrated an MP level of 4.7 ± 3.5 particle/L found in tropical stormwater runoff. Levels of MPs in runoff are expected to vary based on land use patterns and human activities. Piñon-Colin et al. (2020) determined the presence of MPs in stormwater runoff in Mexico, with abundances ranging from 66 particles/L to 191 particles/L. Further, in stormwater runoff, MP concentrations were measured at 67.7 ± 11.3 particles/L in commercial areas, 23 ± 10.3 particles/L in residential areas, and 168.7 ± 37.1 particles/L in highways (Parameswarappa Jayalakshmamma et al. 2023). The levels of MPs (typically range in size from 1 to 125 µm) vary significantly among different urban land use patterns, with highways exhibiting the highest concentrations, followed by residential and commercial areas.

Fate and Transport of Microplastics in Stormwater Runoff

The environmental fate of MPs is recognized by complex processes, including weathering, biofilm formation, sedimentation, and biologic degradation (Wei et al. 2023). In the environment, MPs could originate from plastic-containing waste and/or undergo further degradation via different abiotic processes (such as photodegradation by UV radiation, sunlight-based thermal degradation, mechanical degradation, and chemical-catalyzed decomposition) and biotic degradation (Ky et al. 2023; Zhang et al. 2021). The biodegradation facilitated by enzymatic breakdown by microbes plays a crucial role in degrading and converting MPs into smaller debris and fragments. Several environmental factors, i.e., temperature, pH, UV radiation, reactive oxygen species (ROS), and the presence of inorganic and organic substances, can significantly impact the degradation, stability, and environmental transport of MP particles (Nguyen et al. 2022a; Van-Re et al. 2023). Increasing rainfall frequency can promote the mobilization of MPs that have accumulated on soil, thereby increasing the number of MPs transported by stormwater runoff (Sang et al. 2021). During rainfall events, MPs can be mobilized from various sources, such as urban surfaces, roadways, and soil.

Another report recognized that water shear stress (refers to the force per unit area exerted by flowing water on a surface) can enhance the generation of nanoplastics through mechanisms, such as crushing and micro-crack propagation (Enfrin et al. 2020). Key pathways in transferring MP contamination to aquatic ecosystems include wastewater effluent discharge, atmospheric deposition, and stormwater runoff (Ali et al. 2024; Nguyen et al. 2024b). Additionally, the retention time of MPs in stormwater runoff could influence the hydrolysis of MPs. UV exposure and biodegradation can promote the aging process of MPs in stormwater runoff. Once in the stormwater runoff, MPs are transported through drainage systems, streams, and rivers (Sewwandi et al. 2024; Wang et al. 2022). Their movement is influenced by factors, such as density, particle size, and hydrodynamic forces. The size of MPs influences their mobility in stormwater runoff, e.g., smaller particles (sizes less than 50 µm) are easily transported to receiving water bodies via urban road stormwater runoff (Klöckner et al. 2020). The fate of MPs may also depend on various other factors, including polymer type, size, and morphology. Smaller MPs may be more readily transported into deeper soil layers. In agricultural systems, the fate of MPs can also be influenced by environmental conditions, properties of plant–soil interactions, and agricultural management practices. MPs can enter aquatic ecosystems through non-point sources, with stormwater runoff being a significant pathway (Werbowski et al. 2021). The discharge of MPs via stormwater runoff is highly variable over time, often peaking during and immediately after rainfall events. The abundance of MPs was significantly higher during the wet season compared to the dry season (Fan et al. 2022). The concentration and type of MPs can vary depending on factors like the season, weather patterns,

Table 1 Global reports on microplastic pollution in stormwater runoff

Location	Media	Concentration	Size	Main polymers	Shape	Remarks	References
Canada	Catchment/ stormwater	15.4 particles/L	125–5000 µm	PP, PVC, PE, PTFE, PA, PU, Nylon, PET	Fibers, films, fragments, foams, bundles	MPs linked to urban sources	(Grbić et al. 2020)
US	Urban runoff	23 ± 10.3–168.7 ± 37.1 particles/L	1–125 µm	PS, PA, PTFE, HDPE, PMMA, EVA, cellophane, methylcellulose	Fibers, fragments, films	Stormwater runoff is a crucial pathway for MP transport	(Parameswarappa Jayalakshmamma et al. 2023)
US	Stormwater runoff/urban	8.3 ± 6.9 particles/L (1.1–24.6 particles/L)	< 125 µm	PES, PE, PET, PP	Fibers, rubber, fragments	Strategies for stormwater elimination need to be considered	(Werbowski et al. 2021)
Mexico	Catchment/ road runoff	167 particles/L (66–191 particles/L)	25–5000 µm	PE, PA, PET, PS, PP	Fragments, fibers, films, granules	Stormwater runoff is a primary source	(Piñon-Colin et al. 2020)
China	Urban stormwater/ sediments	1107.7 ± 422.1 particles/kg	< 1000 µm	PP, PET, PE, PS	Fibers, fragments, films	High MP pollution from main roads	(Niu et al. 2024)
China	Stormwater drainage/ entrance	2–22 particles/L	37–5000 µm	PE, PET, PP, PVC, PS	Fragments, fibers, granules, films	Land-based MPs enter freshwater	(Sang et al. 2021)
Hong Kong	Stormwater drainage/ outlet	1.4–6.8 particles/L	54–1000 µm	PE, PP, nylon 6/6	Fibers, fragments, pellets	Bioaccumulation of MPs was observed in marine fish	(Mak et al. 2020)
Japan	Catchment/ road runoff	81–292 particles/L	10–5000 µm	AS, PET, EVA, PEPD, PEP, PS, PE, PP	Fibers, flakes	Plastic debris from automobile tire wear	(Sugiura et al. 2021)
Korea	Stormwater runoff/ urban area	68–568 particles/L (industrial) 54–639 particles/L (residential)	20–200 µm	PP, PE	Fragments, fibers	Urban stormwater is a crucial transporter of MP contaminations into aquatic ecosystems	(Cho et al. 2023)
Thailand	Tropical stormwater runoff	4.7 ± 3.5 particle/L 0.3–17.3 particles/L	> 300 µm	PE, PP, rubber, PVC, PEP, PS	Fibers, films, fragments, foams	Abundances: industrial > transportation > commercial > residential	(Xue et al. 2023)
Iran	Catchment/ stormwater runoff	1.8 particles/L (1.2–3 particles/L)	< 5000 µm	n/a	Fibers, fragments, filaments, granules, foams	Fishing and port-related commercial activities	(Hajiouni et al. 2022)
Australia	Stormwater runoff/metropolitan	24–35 particles/L	125–960 µm	PP, PE, PS, PVC, PES	Fragments, fibers	Ecological threat indices of MP polymers related to land use	(Kabir et al. 2024)
Italy	Stormwater runoff/ highway	11,932 ± 151–18,966 ± 191 particles/L	5–100 µm	VE, PA6, PES, fluorocarbon	Ellipsoids	High MP pollution	(Rosso et al. 2022)
Denmark	Catchment/ponds	0.5–22.9 particles/L	10–2000 µm	PP, PE, PVC, PES, PS	n/a	Land-based sources	(Liu et al. 2019a)
Denmark	Stormwater pond	270 particles/L	10–500 µm	PES, PP, acrylic, PA, PE	Fragments, fibers	As high as in the sediment	(Olesen et al. 2019)

Table 1 (continued)

Location	Media	Concentration	Size	Main polymers	Shape	Remarks	References
France	Suburban catchment/urban runoff	29 particles/L (3–129 particles/L)	> 80 µm	PE, PP, PS	Fibers	Primarily residential, characteristic of moderately dense urban zones, with fibers from larger object breakdown	(Treilles et al. 2021)
Sweden	Highway runoff	230 particles/L (42– 8577 particles/L)	20–100 µm	PP, EVA, EPDM, rubber	n/a	Highway stormwater is an MP source	(Lange et al. 2022)
South Africa	Stormwater outlets/coastal zones	0.15 ± 0.01 particles/L	1000–2000 µm	PES, PS, PP, PET	Fibers, fragments, films	Coastal stormwater is a potential source of MPs	(Ariefdien et al. 2024)

MPs Microplastics, *EPDM* Ethylene propylene diene rubber, *PA* Polyamide, *EVA* Ethylene–vinyl acetate, *PEP* Polyethylene polypropylene copolymer, *PU* Polyurethane, *PVC* Polyvinyl chloride, *PTFE* Polytetrafluoroethylene, *VE* Vinyl ester, *PA6* Polyamide 6, *PMMA* Poly(methyl methacrylate), *PEPD* Polyethylene polypropylene diene, *AS* Acrylonitrile styrene, *PES* Polyester

and preceding dry periods that allow MPs to accumulate on surfaces. The seasonal variations in MP abundance can be attributed to the effect of plastic production, land use, and fluctuations in regional precipitation (Cho et al. 2023; Fan et al. 2022). Thus, identifying the migration pathways (e.g., surface runoff, drainage systems, infiltration, and outflow to water bodies) of MPs is indeed a crucial step in effectively mitigating MP pollution. Understanding how MPs move through various environments allows for targeted interventions and strategies to prevent their release, reduce their entry into ecosystems, and ultimately minimize their impact on environmental and human health. Further examination of the transport mechanisms of MPs, including how they move through various environmental compartments (i.e., water, air, soil), would help predict their fate and potential impacts more accurately.

Nature-Based Solutions for Microplastic Removal

Wastewater treatment plants prevent MPs from entering the environment (Nguyen et al. 2022a). In conventional technologies, MPs are effectively retained during wastewater treatment, primarily through mechanical treatment and sludge-settling processes (Murphy et al. 2016). It has also been demonstrated that stormwater retention structures can effectively remove large MPs (Table 2). This efficient removal can help reduce the threat of MPs releasing plastic additives into aquatic ecosystems (Smyth et al. 2021). Stormwater MP removal can be obtained via various approaches, including filtration, ponds or wetlands, bioretention (such as rain gardens and bioretention cells), and sedimentation/filtration-based SUDS (García-Haba et al. 2023; Lange et al. 2021; Liu et al. 2019b; Stang et al. 2022). For instance, wetlands and retention ponds have been shown to remove 28–55% and 85–99% of MPs, respectively (Stang et al. 2022). These methods are remarkably suggested for areas with high fibrous MP content. Filtration systems and bioretention have demonstrated similar performance, with removal efficiencies greater than 84% for MPs (Stang et al. 2022). Yet, natural filtration systems can trap larger MPs but may be less efficient for smaller particles. The filtering capacity of natural systems depends on particle size and the system's design, which may not always be optimized for removing very fine MPs. With regards to bioretention cells, contaminants could be removed through a combination of chemical, physical, and biologic processes (Fig. 2). To prevent the discharge of MPs from stormwater runoff, SUDS can indeed be part of the effective approach (Monira et al. 2021). Filtration and sedimentation-based SUDS solutions have been recognized to treat MPs efficiently (García-Haba et al. 2023). SUDS are engineered nature-aided approaches

Table 2 Summary of nature-based microplastic removal studies in stormwater runoff

Location	Method	Concentration		Removal efficiency (%)	Remarks	Refs
		Inlet	Outlet			
Canada	Bioretention Filter media (62% sand, 38% silt and clay)	186 ± 173 particles/L	31 ± 35 particles/L	84%	It is effective in filtering out MPs	(Smyth et al. 2021)
US	Aged bioretention systems	448 particles/100 g (surface layer, 0–5 cm)	136 particles/100 g (depth layer, 10–15 cm)	Suitability (decreased significantly)	MPs are accumulated mainly in the filter media top layer (trapped in the filter media)	(Lange et al. 2023)
US	Bioretention Filter media (70% sandy loam, 10% clay, 20% compost)	1.9 particles/L	0.07 particles/L	95%	Successfully removed of anthropogenic debris MP pollution mitigation strategy	(Werbowski et al. 2021)
US	Bioretention (rain garden)	1.6 particles/L	0.16 particles/L	90%	Stormwater management option	(Gilbreath et al. 2019)
Sweden	Bioretention filters Pilot scale	30–147 µg/L	< 10%	> 83%	> 10 µm-sized debris was effectually trapped in bioretention filters The filters' performance over time should be assessed	(Johansson et al. 2024)
Sweden	Bioretention Filter media (vegetated sand-based filter)	4.06 particles/L	0.38 particles/L	97%	Filter efficiently removed MPs	(Lange et al. 2021)
Finland	Biofilter structures	5 g/250 mL (tap water)	Not detected (no MPs)	100%	Solutions to manage stormwater Plant roots created pathways that facilitated MP accumulation along root channels	(Kuoppamäki et al. 2021)
Belgium	Horizontal subsurface-constructed wetlands	4–10.3 particles/L	n/a	88%	Constructed wetlands are efficient filters for MPs (in tertiary treatment) Preventing their entry into vulnerable aquatic ecosystems	(Wang et al. 2020)
Poland	Constructed wetlands	0.56–104.77 µg/m^3	0–23.61 µg/m^3	77.2–100%	Effective rainwater management Efficacy based on the bed's hydraulic load	(Jakubowicz et al. 2022)
Denmark	Stormwater retention ponds	$3.47 \times 10^{-1} - 1.85 \times 10^{3}$	7.87×10^{-2} –2.59 10^{2}	77–95%	Stormwater retention ponds are effective in MP removal	(Rasmussen et al. 2024)

Table 2 (continued)

Location	Method	Concentration		Removal efficiency (%)	Remarks	Refs
		Inlet	Outlet			
Sweden	Horizontal flow sand filters (lab scale, length 25 cm)	PA(652,000) PE(32,000) PP (121,000) PET (183,000) particle counts	PA(2080) PE(260) PP (440) PET (220) particle counts	99%	It can be effective in retaining MPs MP size (length and width) affects filter retention	(Rullander et al. 2023)
Australia	Floating wetlands	595 ± 120 particles/kg (sediments)	320 ± 42 particles/kg (sediments)	46%	Long-term sink (MP pollution)	(Ziajahromi et al. 2020)

PA Polyamide, *PP* Polypropylene, *PET* Polyethylene terephthalate, *PA* Polyamide, *MPs* Microplastics

for sustainable urban stormwater management. They are designed to improve water quality, prevent diffuse pollution, and tackle this global problem. Overall, filtration/sedimentation-based systems like constructed wetlands, natural ponds, bioretention cells, rain gardens, SUDS, and permeable pavements have demonstrated effectiveness in retaining a significant number of MPs. These eco-friendly approaches mitigate MP pollution in urban environments (García-Haba et al. 2023). Furthermore, constructed wetlands-based treatment plants are often carried out to provide tertiary treatment (Wang et al. 2020).

As ponds can effectively retain MPs in their sediments, many authors have reported the significant potential of ponds for MP elimination (Liu et al. 2019a, 2019b; Olesen et al. 2019). The authors have revealed a higher MP level in the sediment samples than in the pond water samples, indicating that sediments acted as an important mechanism for MP removal (Olesen et al. 2019). With regards to stormwater runoff treatment wetlands, they are indeed one of the essential solutions for treating runoff stormwater (Fig. 3). Numerous studies have focused on using constructed wetlands for treating stormwater and wastewater (Ky et al. 2020; Wang et al. 2020). The primary mechanisms for eliminating pollutants include photodegradation, aging, anaerobic and aerobic biodegradation, plant uptake and subsequent alteration, and sediment adsorption (Monira et al. 2021). Wetlands are known to have a similar role to retention ponds in that they provide retention time for contaminant settling. Wetlands also involve plant/vegetation, contributing to additional pollutant treatment based on ecological interactions (Nguyen et al. 2023; Pramanik et al. 2020). However, the efficiency of these systems can be influenced by the design, maintenance, and the specific vegetation used. In some typical cases, the removal efficiency of MP from stormwater using wetlands has been reported to range from 28 to 88% (Pramanik et al. 2020; Wang et al. 2020), but it can reach a range between 77 and 100% depending on the type of polymer (Jakubowicz et al. 2022). Remarkably, phytoremediation techniques, such as constructed wetlands (e.g., surface flow wetlands, subsurface flow wetlands), offer a green and eco-friendly solution (e.g., low-energy solution) for pollutant removal (Chand & Suthar 2024; Ky et al. 2020).

In cases where urban stormwater management is implemented before release into the aquatic environment, nature-based techniques, like bioretention cells and rain gardens, are usually applied (Johansson et al. 2024; Rullander et al. 2023). Werbowski et al. (2021) discovered that the rain garden effectively eliminated anthropogenic debris, including MPs, indicating that rain gardens warrant further investigation as a viable strategy for mitigating MP pollution. These methods often prioritize easily constructed filtration units. Bioretention systems have significantly reduced levels of MP debris/particles (more than 125 µm in size). For another

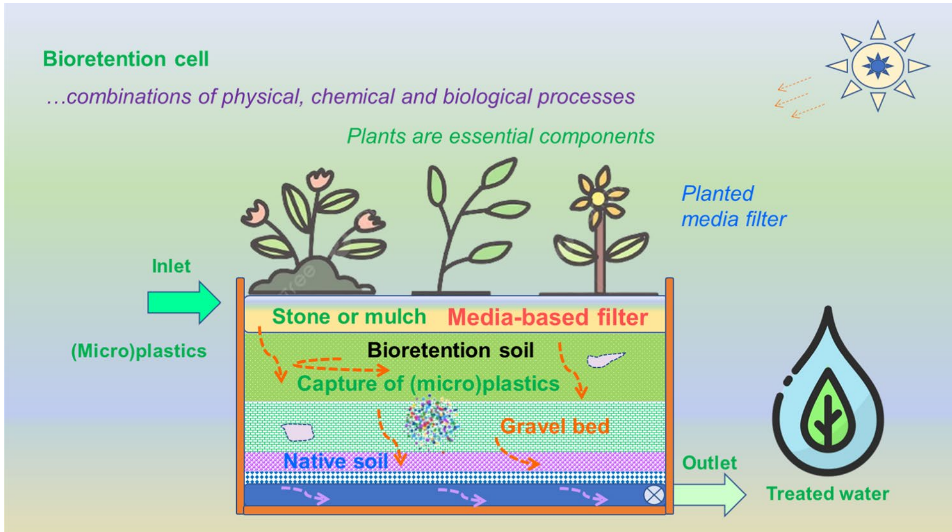


Fig. 2 Bioretention cell-based microplastic removal

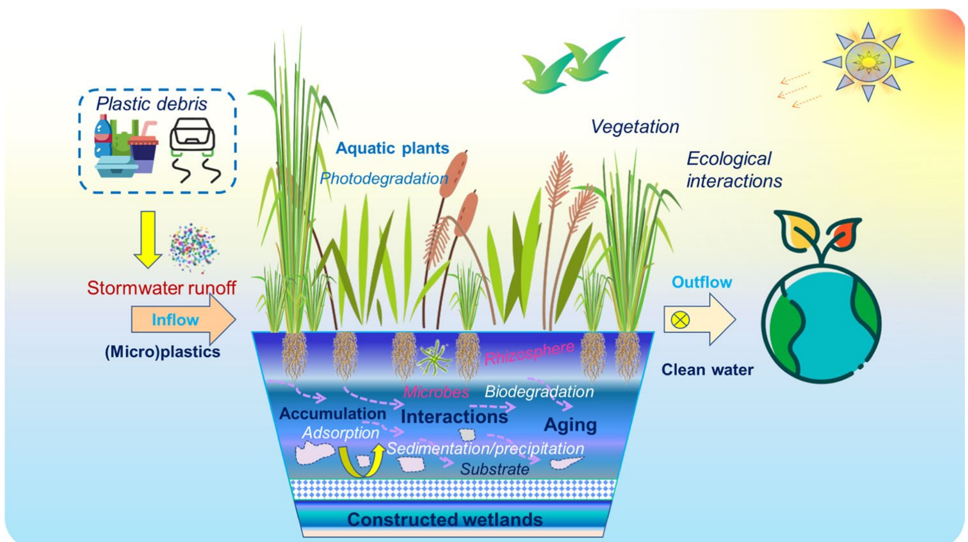


Fig. 3 Constructed wetland-based microplastic removal

instance, a rain garden treating road stormwater runoff in California, US, was reported to reduce MP concentrations by 83–95% (Gilbreath et al. 2019; Österlund et al. 2023). Contaminated water from different sources is popularly treated using filtration-based solutions, where the water flows pass through a porous structural media (Nguyen et al. 2024a; Smyth et al. 2021). The filtration technique is based on passing stormwater via a filter media (sand, gravel, peat, anthracite, or crushed granite) that retains contaminants while allowing the remaining water flows to go through to the discharge point.

For more detail, it is evident that bioretention cells are the most typically employed owing to their design flexibility and potential for reducing MPs from runoff. Bioretention cells, which are planted media filters, are created to reduce the volume of stormwater flows while removing micropollutants such as MPs through various physical and biogeochemical processes (Davis et al. 2009; Lange et al. 2023; Smyth et al. 2021). For instance, bioretention filters incorporating plants such as *Armeria maritima, Juncus effusus, Hippophae rhamnoides, Festuca rubra*, and sorbents have proven effective in removing pollutants from stormwater (Johansson et al. 2024). Notably, the greater than 10 µm-sized MPs were effectively trapped in these bioretention filters (Johansson et al. 2024). Bioretention filters are usually referred to as sustainable removal facilities that are planned to prevent polluted stormwater. Gilbreath et al. (2019) calculated an average removal of 91% between the inlet and outlet of the bioretention structures. MP treatment efficiencies by particle size were determined as follows: 100% for MPs larger than 500 µm; 81% for MPs ranging from 355 µm to 500 µm; and 55% for MPs range 125 µm to 355 µm. Bioretention rain gardens are used for MP treatment, because they effectively filter and retain particles from stormwater, especially larger

MPs (Gilbreath et al. 2019; Lange et al. 2021). The varying treatment efficiencies by particle size are due to the physical properties of the filtration media, including pore size and permeability, which are more effective at capturing larger particles. Smaller MPs are more challenging to remove, leading to lower treatment efficiencies for these particles. Furthermore, bioretention-based systems are commonly applied green infrastructure units that use engineered (bioretention) soil media. This media typically involves a mixture of sandy loam, sand, and loamy sand, designed for stormwater capture and treatment purposes (Tirpak et al. 2021). MPs accumulate and attach to the surface layers of bioretention filter media. This accumulation can occur due to significant processes, e.g., filtration, sorption, sedimentation, biodegradation, uptake by plants and their roots, and volatilization (Davis et al. 2009; Johansson et al. 2024; Lange et al. 2023). Thus, these processes positively influence the efficiency of MP removal from stormwater in bioretention filter systems.

Recommendations

To effectively address stormwater-related MP pollution, several key actions (e.g., enhanced monitoring, source control, innovative treatment technologies, policy development, public awareness) and areas for further work are necessary. Research could focus on developing advanced filtration materials, such as nanofibers or membranes, specifically designed to capture MPs of varying sizes. These materials could be integrated into stormwater management systems to enhance MP removal efficiency. Future research can address existing gaps and contribute to a more comprehensive understanding of MP pollution and its management.

1. MPs can impact the uptake and accumulation of heavy metal(loid)s within biota and plant species, with potential variation depending on the additives and polymers used. The important interactions between MPs from various sources, such as these heavy metal(loid)s and plants, should be carefully reported and investigated to understand potential risks better. Understanding MPs' dynamics and potential threats in stormwater environments requires in-depth examination.

2. Further studies are required to explore the long-term impacts of MPs on ecosystems and to conduct a cost–benefit analysis of excellent strategies for eliminating MP inputs into stormwater flows. This includes the persistence and environmental fate of MPs, their impacts on biodiversity, and the social effectiveness of various mitigation measures in preventing and reducing MP pollution in aquatic environments.

3. Historically, urban stormwater management prioritized quantity control combined with sewer systems. However, recent strategies have been changed towards the adoption of blue-green infrastructure. There is a pressing need to develop reliable and cost-effective technologies to remove MP pollutants from stormwater, allowing for their safe discharge into open waterways or potential reuse. Further research is advised to investigate the sustainability of wetlands, bioretention systems, or SUDS for MP treatment. The performance of bioretention systems, such as rain gardens and bioswales, should be studied for their ability to capture MPs from stormwater runoff, with a focus on soil composition and vegetation. The potential of SUDS to manage MPs alongside other pollutants in urban areas should be evaluated, emphasizing the integration of green infrastructure solutions like permeable pavements and vegetated swales to enhance MP removal while promoting ecosystem health and resilience.

4. Develop hybrid-constructed wetlands that combine traditional phytoremediation with advanced filtration techniques or microbial treatments specifically targeting MPs. Research could optimize plant species selection and substrate composition for enhanced MP capture and degradation. These perspectives emphasize innovative, interdisciplinary approaches to controlling MPs in stormwater, focusing on developing new technologies, leveraging natural processes, and enhancing community involvement.

5. Additionally, a SWOT analysis could be conducted for each treatment method to provide a comprehensive evaluation, offering valuable insights into strengths, weaknesses, opportunities, and threats, which can guide informed decision-making. Therefore, based on SWOT analysis, future work should focus on leveraging the strengths of current methods while addressing identified weaknesses and threats. Additionally, exploring new opportunities and refining design criteria will enhance the effectiveness and applicability of the novel solutions.

6. Several smaller MPs, particularly nanoplastics, may evade capture by conventional removal systems and present the highest environmental risks. These tiny particles and the release of plastic additives can increase toxicity to aquatic organisms and cause health threats (Minh-Ky et al. 2023; Wang et al. 2021). Therefore, special attention and innovative strategies are required to manage nanoplastic pollution and mitigate its environmental impacts effectively.

7. Since stormwater MP levels vary depending on the surrounding environment, it is crucial to establish MP level thresholds and appropriate regulations to mitigate potential adverse (eco)toxicological impacts (Stang et al. 2022). To effectively manage MPs in stormwater runoff, it is imperative to implement more relevant policies, regulations, and measures. This necessitates global, national, and regional cooperation and local action.

8. Controlling MP pollution requires source prevention and effective stormwater management strategies. Continuous monitoring and predicting MPs originating from non-point sources, considering rainfall characteristics and land

use patterns, is essential to understanding the behavior/fate of MPs as they move from terrestrial ecosystems to aquatic ecosystems (Tran et al. 2023). Developing detailed guidelines for MP monitoring in stormwater runoff is imperative, mainly focusing on sample collection methods that account for the temporal variability of MP during stormwater runoff. These guidelines will ensure data compatibility among studies.

9. MP pollution control necessitates a multifaceted approach, including legislative measures to regulate the production of single-use plastics (SUPs) or ban the addition of microbeads (manufactured solid plastic particles) in personal care products. Additionally, policies for improving plastic-related waste management, strengthening recycling efforts, and promoting upcycling of plastic waste are essential components of effective MP pollution mitigation strategies. Formulating comprehensive regulations, policies, and measures is necessary to systematically control/manage the challenges associated with MPs migrating from land to aquatic environments. Such initiatives are crucial for effectively addressing MP pollution and minimizing its environmental impact.

Conclusion

Stormwater-related MP contamination has garnered significant attention, underscoring the importance of fully understanding MPs in stormwater runoff. This study critically reviews global occurrence, fate, transport, and the risk/challenge to human health associated with ecological concerns and nature-based solutions. The global occurrence levels of MPs in stormwater runoff range from 1.2–3 particles/L to 11,932 ± 151–18,966 ± 191 particles/L, depending on various factors, such as local sources, land use, and meteorological conditions. Stormwater serves as a significant route for MPs to enter aquatic ecosystems. Therefore, MPs' transport and potential effects from stormwater runoff to ecosystems can have adverse consequences.

MPs can contaminate groundwater/drinking water, accumulate in the food chain/web, and release hazardous chemical compounds that can lead to various illnesses. There is a threat that MPs will accumulate at multiple trophic levels in the food chain/web. This raises concerns about the influence of emerging microcontaminants on human health and environmental matrices. Understanding how MPs interact with other micropollutants in stormwater runoff is essential for evaluating their contaminant transport behavior.

MP removal from stormwater is essential to mitigate its contamination and the associated environmental and ecological impacts. Various stormwater treatment methods for MP reduction have been explored based on physical, biologic, or chemical mechanisms. These methods include bioretention cells, rain gardens, wetlands or ponds, and filtration/sedimentation-based SUDS. They are nature-based solutions commonly used in stormwater treatment systems to remove MPs effectively. Bioretention systems, consisting of engineered filter media and vegetation, have been mainly implemented for MP pollution control in stormwater runoff. Studies on bioretention cells, retention ponds, and filtration have demonstrated removal efficiencies ranging from > 83% to 99%. In contrast, wetlands have shown removal efficiencies ranging from 28 to 88%. These sustainable urban systems minimize the environmental impact of stormwater runoff and protect ecosystems from pollution. In short, such strategies leverage the natural capabilities of ecosystems to effectively filter and capture MPs, leading to a substantial reduction in pollution from stormwater runoff.

This study on the global occurrence and environmental fate of MPs in stormwater runoff highlights significant implications for human health and ecological concerns, but several limitations constrain it. The geographic scope is skewed, leading to potential biases, while data gaps hinder comprehensive analysis. Additionally, the study relies on existing toxicological assessments that may not fully encompass the range of effects on human and ecosystem health. The ecological impacts discussed may not apply uniformly across different environments, and the feasibility of proposed mitigation strategies remains underexplored. Moreover, interactions between MPs and other emerging contaminants in stormwater runoff are not fully addressed, pointing to the need for more integrated research efforts. Future research should expand the geographic and temporal scope of studies on MPs in storm water runoff by conducting long-term analyses to capture seasonal and event-driven variations. Additionally, investigations should focus on the interactions between MPs and other emerging contaminants, such as heavy metals and pharmaceuticals, to better understand the combined environmental and health risks. This approach would provide a more comprehensive assessment and inform the development of more effective and integrated mitigation strategies. For example, studies have shown that MPs can adsorb heavy metals, such as cadmium and lead, from storm water runoff, increasing their persistence and bioavailability in aquatic ecosystems. This combined effect may amplify toxicity to aquatic organisms and pose a risk of entering the food chain. Understanding these interactions is crucial for developing effective solutions to remove both MPs and associated contaminants.

Author contributions Van-Hiep Hoang contributed to Methodology, Data curation, Investigation, Resources, and Writing – original draft. Minh-Ky Nguyen contributed to Conceptualization, Methodology, Data curation, Resources, Investigation, Visualization, and Writing – original draft – review & editing. Tuan-Dung Hoang contributed to Data curation, Visualization, and Writing – review & editing. Hoang-Lam Nguyen contributed to Conceptualization, Data curation, Visualization,

and Writing – review & editing. Chitsan Lin contributed to Investigation, Data curation, and Writing – review & editing. Balal Yousaf contributed to Data curation, Visualization, and Writing – review & editing. Minh Cuong Ha contributed to Data curation and Writing – review & editing. Vu Khac Hoang Bui contributed to Data curation and Writing – review & editing. Minh-Thuan Pham contributed to Investigation and Writing – review & editing. Soon W. Chang contributed to Investigation, Data curation, and Writing – review & editing. D. Duc Nguyen contributed to Supervision, Investigation, Data curation, Resources, and Writing – review & editing.

Data availability The author confirms that all data generated or analysed during this study are included in this published article.

Declarations

Conflict of interest The authors declare no conflict of interest.

References

Ali N, Khan MH, Ali M, Ahmad S, Khan A, Nabi G, Ali F, Bououdina M, Kyzas GZ (2024) Insight into microplastics in the aquatic ecosystem: properties, sources, threats and mitigation strategies. Sci Total Environ 913:169489

Ariefdien R, Pfaff M, Awe A, Sparks C (2024) Stormwater outlets: a source of microplastics in coastal zones of Cape Town. South Africa Marine Pollution Bulletin 198:115800

Bailey K, Sipps K, Saba GK, Arbuckle-Keil G, Chant RJ, Fahrenfeld NL (2021) Quantification and composition of microplastics in the Raritan Hudson Estuary: comparison to pathways of entry and implications for fate. Chemosphere 272:129886

Campanale C, Galafassi S, Savino I, Massarelli C, Ancona V, Volta P, Uricchio VF (2022) Microplastics pollution in the terrestrial environments: Poorly known diffuse sources and implications for plants. Sci Total Environ 805:150431

Chand N, Suthar S (2024) Source, fate, toxicity, and remediation of micro-plastic in wetlands: a critical review. Watershed Ecol and the Environ 6:41–53

Cho Y, Shim WJ, Ha SY, Han GM, Jang M, Hong SH (2023) Microplastic emission characteristics of stormwater runoff in an urban area: intra-event variability and influencing factors. Sci Total Environ 866:161318

Davis AP, Hunt WF, Traver RG, Clar M (2009) Bioretention technology: overview of current practice and future needs. J Environ Eng 135(3):109–117

de Jesus Piñon-Colin T, Rodriguez-Jimenez R, Rogel-Hernandez E, Alvarez-Andrade A, Wakida FT (2020) Microplastics in stormwater runoff in a semiarid region, Tijuana. Mexico Sci Total Environ 704:135411

Devereux R, Ayati B, Westhead EK, Jayaratne R, Newport D (2023) Impact of the Covid-19 pandemic on microplastic abundance along the River Thames. Mar Pollut Bull 189:114763

Enfrin M, Lee J, Gibert Y, Basheer F, Kong L, Dumée LF (2020) Release of hazardous nanoplastic contaminants due to microplastics fragmentation under shear stress forces. J Hazard Mater 384:121393

Fahrenfeld NL, Arbuckle-Keil G, Beni NN, Bartelt-Hunt SL (2019) Source tracking microplastics in the freshwater environment. TrAC, Trends Anal Chem 112:248–254

Fan Y, Zheng J, Deng L, Rao W, Zhang Q, Liu T, Qian X (2022) Spatiotemporal dynamics of microplastics in an urban river network area. Water Res 212:118116

Fang Q, Niu S, Yu J (2021) Characterising microplastic pollution in sediments from urban water systems using the diversity index. J Clean Prod 318:128537

Foley CJ, Feiner ZS, Malinich TD, Höök TO (2018) A meta-analysis of the effects of exposure to microplastics on fish and aquatic invertebrates. Sci Total Environ 631:550–559

García-Haba E, Hernández-Crespo C, Martín M, Andrés-Doménech I (2023) The role of different sustainable urban drainage systems in removing microplastics from urban runoff: a review. J Clean Prod 411:137197

Geyer R, Jambeck JR, Law KL (2017) Production, use, and fate of all plastics ever made. Sci Adv 3(7):e1700782

Gilbreath A, McKee L, Shimabuku I, Lin D, Werbowski LM, 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. J Sustain Water Built Environ 5(4):04019004

Grbić J, Helm P, Athey S, Rochman CM (2020) Microplastics entering northwestern Lake Ontario are diverse and linked to urban sources. Water Res 174:115623

Hajiouni S, Mohammadi A, Ramavandi B, Arfaeinia H, De-la-Torre GE, Tekle-Röttering A, Dobaradaran S (2022) Occurrence of microplastics and phthalate esters in urban runoff: a focus on the Persian Gulf coastline. Sci Total Environ 806:150559

Hanun JN, Hassan F, Jiang J-J (2021) Occurrence, fate, and sorption behavior of contaminants of emerging concern to microplastics: influence of the weathering/aging process. J Environ Chem Eng 9(5):106290

Hoang V-H, Nguyen M-K, Hoang T-D, Ha MC, Huyen NTT, Bui VKH, Pham M-T, Nguyen C-M, Chang SW, Nguyen DD (2024) Sources, environmental fate, and impacts of microplastic contamination in agricultural soils: a comprehensive review. Sci Total Environ 950:175276

Horton AA, Barnes DKA (2020) Microplastic pollution in a rapidly changing world: implications for remote and vulnerable marine ecosystems. Sci Total Environ 738:140349

Jakubowicz P, Fitobór K, Gajewska M, Drewnowska M (2022) Detection and removal of priority substances and emerging pollutants from stormwater: case study of the kołobrzeska collector, gdańsk. Poland Sustain 14(3):1105

Johansson G, Fedje KK, 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. J Hazard Mater 468:133532

Kabir SMA, Bhuiyan MA, Zhang G, Pramanik BK (2024) Microplastic distribution and ecological risks: investigating road dust and stormwater runoff across land uses. Environ Sci: Adv 3(1):62–75

Klöckner P, Seiwert B, Eisentraut P, Braun U, Reemtsma T, Wagner S (2020) Characterization of tire and road wear particles from road runoff indicates highly dynamic particle properties. Water Res 185:116262

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. Wiley Online Library, Hoboken

Ky NM, Rakib MRJ, Lin C, Hung NTQ, Le V-G, Nguyen H-L, Malafaia G, Idris AM (2023) A comprehensive review on ecological effects of microplastic pollution: an interaction with pollutants in the ecosystems and future perspectives. TrAC, Trends Anal Chem 168:117294

Ky, N.M., Hung, N.T.Q., Manh, N.C., Lap, B.Q., Dang, H.T.T., Ozaki, A. 2020. Assessment of nutrients removal by constructed wetlands using Reed Grass (*Phragmites australis* L.) and Vetiver Grass (*Vetiveria Zizanioides* L). **65**(1), 149–156.

Lange K, Magnusson K, Viklander M, Blecken G-T (2021) Removal of rubber, bitumen and other microplastic particles from stormwater by a gross pollutant trap-bioretention treatment train. Water Res 202:117457

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. Sci Total Environ 809:151151

Lange K, Furén R, Österlund H, Winston R, Tirpak RA, 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

Le V-G, Nguyen H-L, Nguyen M-K, Lin C, Hung NTQ, Khedulkar AP, Hue NK, Trang PTT, Mungray AK, Nguyen DD (2024a) Marine macro-litter sources and ecological impact: a review. Environ Chem Lett 22:1257–1273

Le V-G, Nguyen M-K, Nguyen H-L, Thai V-A, Le V-R, Vu QM, Asaithambi P, Chang SW, Nguyen DD (2024b) Ecotoxicological response of algae to contaminants in aquatic environments: a review. Environ Chem Lett 22(2):919–939

Liu F, Olesen KB, Borregaard AR, Vollertsen J (2019a) Microplastics in urban and highway stormwater retention ponds. Sci Total Environ 671:992–1000

Liu F, Vianello A, Vollertsen J (2019b) Retention of microplastics in sediments of urban and highway stormwater retention ponds. Environ Pollut 255:113335

Mak CW, Tsang YY, Leung MM-L, Fang JK-H, Chan KM (2020) Microplastics from effluents of sewage treatment works and stormwater discharging into the Victoria Harbor. Hong Kong Marine Pollution Bulletin 157:111181

Malli A, Shehayeb A, Yehya A (2023) Occurrence and risks of microplastics in the ecosystems of the Middle East and North Africa (MENA). Environ Sci Pollut Res 30(24):64800–64826

Minh-Ky N, Lin C, Nguyen H-L, Le V-G, Haddout S, Um M-J, Chang SW, Nguyen DD (2023) Ecotoxicity of micro-and nanoplastics on aquatic algae: facts, challenges, and future opportunities. J Environ Manage 346:118982

Monira S, Bhuiyan MA, Haque N, Shah K, Roychand R, Hai FI, Pramanik BK (2021) Understanding the fate and control of road dust-associated microplastics in stormwater. Process Saf Environ Prot 152:47–57

Monira S, Roychand R, Bhuiyan MA, Hai FI, Pramanik BK (2022) Identification, classification and quantification of microplastics in road dust and stormwater. Chemosphere 299:134389

Murphy F, Ewins C, Carbonnier F, Quinn B (2016) Wastewater treatment works (WwTW) as a source of microplastics in the aquatic environment. Environ Sci Technol 50(11):5800–5808

Nguyen MK, Hadi M, Lin C, Nguyen H-L, Thai V-B, Hoang H-G, Vo D-VN, Tran H-T (2022a) Microplastics in sewage sludge: distribution, toxicity, identification methods, and engineered technologies. Chemosphere 308:136455

Nguyen MK, Lin C, Hung NTQ, Vo D-VN, Nguyen KN, Thuy BTP, Hoang HG, Tran HT (2022b) Occurrence and distribution of microplastics in peatland areas: a case study in Long an province of the Mekong Delta. Vietnam Sci Total Environ 844:157066

Nguyen MK, Hung NTQ, Nguyen CM, Lin C, Nguyen TA, Nguyen H-L (2023) Application of vetiver grass (*Vetiveria Zizanioides* L.) for organic matter removal from contaminated surface water. Bioresour Technol Reports 22:101431

Nguyen M-K, Lin C, Bui X-T, Rakib MRJ, Nguyen H-L, Truong Q-M, Hoang H-G, Tran H-T, Malafaia G, Idris AM (2024) Occurrence and fate of pharmaceutical pollutants in wastewater: insights on ecotoxicity, health risk, and state–of–the-art removal. Chemosphere 354:141678

Nguyen M-K, Rakib MRJ, Lin C, Hwangbo M, Kim J (2024b) Is micro(nano)plastic contamination in wet atmospheric deposition a prominent issue requiring heightened attention? J Hazard Mater 476:135027

Nguyen M-K, Rakib MRJ, Nguyen H-L, Lin C, Malafaia G, Idris AM (2024c) A mini-review on plasticrusts: occurrence, current trends, potential threats, and recommendations for coastal sustainability. Environ Monit Assess 196(2):137

Niu S, Liu C, Yang C, Liu H (2024) Microplastic pollution in urban stormwater inlet sediments influenced by land use type of runoff drainage area. Sci Total Environ 914:170003

Olesen KB, Stephansen DA, van Alst N, Vollertsen J (2019) Microplastics in a stormwater pond. Water 11(7):1466

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. Sci Total Environ 858:159781

Parameswarappa Jayalakshmamma M, Na Nagara V, Borgaonkar A, Sarkar D, Sadik O, Boufadel M (2023) Characterizing microplastics in urban runoff: a multi-land use assessment with a focus on 1–125 µm size particles. Sci Total Environ 904:166685

Piñon-Colin T, Rodriguez-Jimenez R, Rogel-Hernandez E, Alvarez-Andrade A, Wakida FT (2020) Microplastics in stormwater runoff in a semiarid region, Tijuana. Mexico Sci Total Environ 704:135411

Pramanik BK, Roychand R, Monira S, Bhuiyan M, Jegatheesan V (2020) Fate of road-dust associated microplastics and per- and polyfluorinated substances in stormwater. Process Saf Environ Prot 144:236–241

Rasmussen LA, Liu F, Klemmensen NDR, Lykkemark J, Vollertsen J (2024) Retention of microplastics and tyre wear particles in stormwater ponds. Water Res 248:120835

Rosso B, Corami F, Vezzaro L, Biondi S, Bravo B, Barbante C, Gambaro A (2022) Quantification and characterization of additives, plasticizers, and small microplastics (5–100 µm) in highway stormwater runoff. J Environ Manage 324:116348

Rullander G, Lorenz C, Herbert RB, Strömvall A-M, Vollertsen J, Dalahmeh SS (2023) How effective is the retention of microplastics in horizontal flow sand filters treating stormwater? J Environ Manage 344:118690

Sang W, Chen Z, Mei L, Hao S, Zhan C, Zhang bin W, Li M, Liu J (2021) The abundance and characteristics of microplastics in rainwater pipelines in Wuhan. China Sci Total Environ 755:142606

Schernewski G, Radtke H, Hauk R, Baresel C, Olshammar M, Oberbeckmann S (2021) Urban microplastics emissions: effectiveness of retention measures and consequences for the Baltic Sea. Front Mar Sci 8:594415

Sewwandi M, Kumar A, Pallewatta S, Vithanage M (2024) Microplastics in urban stormwater sediments and runoff: an essential component in the microplastic cycle. TrAC, Trends Anal Chem 178:117824

Shruti VC, Pérez-Guevara F, Elizalde-Martínez I, Kutralam-Muniasamy G (2021) Current trends and analytical methods for evaluation of microplastics in stormwater. Trends in Environ Anal Chem 30:e00123

Smyth K, Drake J, Li Y, Rochman C, Van Seters T, Passeport E (2021) Bioretention cells remove microplastics from urban stormwater. Water Res 191:116785

Song YK, Hong SH, Jang M, Han GM, Jung SW, Shim WJ (2017) Combined effects of UV exposure duration and mechanical abrasion on microplastic fragmentation by polymer type. Environ Sci Technol 51(8):4368–4376

Stang C, Mohamed BA, Li LY (2022) Microplastic removal from urban stormwater: current treatments and research gaps. J Environ Manage 317:115510

Sugiura M, Takada H, Takada N, Mizukawa K, Tsuyuki S, Furumai H (2021) Microplastics in urban wastewater and estuarine water: importance of street runoff. Environ Monit and Contam Res 1:54–65
Tirpak RA, Afrooz ARMN, Winston RJ, Valenca R, Schiff K, Mohanty SK (2021) Conventional and amended bioretention soil media for targeted pollutant treatment: a critical review to guide the state of the practice. Water Res 189:116648
Tiwari BR, Lecka J, Pulicharla R, Brar SK (2023) Microplastic pollution and associated health hazards: Impact of COVID-19 pandemic. Current Opinion in Environmental Science & Health 34:100480
Tran H-T, Hadi M, Nguyen TTH, Hoang HG, Nguyen M-K, Nguyen KN, Vo D-VN (2023) Machine learning approaches for predicting microplastic pollution in peatland areas. Mar Pollut Bull 194:115417
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. Environ Pollut 287:117352
Van-Giang L, Nguyen M-K, Nguyen H-L, Lin C, Hadi M, Hung NTQ, Hoang H-G, Nguyen KN, Tran H-T, Hou D, Zhang T, Bolan NS (2023) A comprehensive review of micro- and nano-plastics in the atmosphere: occurrence, fate, toxicity, and strategies for risk reduction. Sci Total Environ 904:166649
Van-Giang L, Nguyen M-K, Lin C, Nguyen H-L, Nguyen TQH, Hue NK, Truong Q-M, Chang SW, Nguyen XH, Nguyen DD (2024) Review on personal protective equipment: emerging concerns in micro(nano)plastic pollution and strategies for addressing environmental challenges. Environ Res 257:119345
Van-Re L, Nguyen M-K, Nguyen H-L, Lin C, Rakib MRJ, Thai V-A, Le V-G, Malafaia G, Idris AM (2023) Organic composts as a vehicle for the entry of microplastics into the environment: a comprehensive review. Sci Total Environ 892:164758
Wang Q, Hernández-Crespo C, Santoni M, Van Hulle S, Rousseau DPL (2020) Horizontal subsurface flow constructed wetlands as tertiary treatment: can they be an efficient barrier for microplastics pollution? Sci Total Environ 721:137785
Wang L, Wu W-M, Bolan NS, Tsang DCW, Li Y, Qin M, Hou D (2021) Environmental fate, toxicity and risk management strategies of nanoplastics in the environment: current status and future perspectives. J Hazard Mater 401:123415
Wang C, O'Connor D, Wang L, Wu W-M, Luo J, Hou D (2022) Microplastics in urban runoff: global occurrence and fate. Water Res 225:119129
Wei L, Yue Q, Chen G, Wang J (2023) Microplastics in rainwater/stormwater environments: influencing factors, sources, transport, fate, and removal techniques. TrAC, Trends Anal Chem 165:117147
Werbowski LM, Gilbreath AN, Munno K, Zhu X, Grbic J, Wu T, Sutton R, Sedlak MD, Deshpande AD, Rochman CM (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
Winiarska E, Jutel M, Zemelka-Wiacek M (2024) The potential impact of nano- and microplastics on human health: understanding human health risks. Environ Res 251:118535
Xue W, Maung GYT, Otiti J, Tabucanon AS (2023) Land use-based characterization and source apportionment of microplastics in urban storm runoffs in a tropical region. Environ Pollut 329:121698
Zhang K, Hamidian AH, Tubić A, Zhang Y, Fang JKH, Wu C, Lam PKS (2021) Understanding plastic degradation and microplastic formation in the environment: a review. Environ Pollut 274:116554
Zhang J, Ding W, Zou G, Wang X, Zhao M, Guo S, Chen Y (2023) Urban pipeline rainwater runoff is an important pathway for land-based microplastics transport to inland surface water: a case study in Beijing. Sci Total Environ 861:160619
Ziajahromi S, Drapper D, Hornbuckle A, Rintoul L, Leusch FDL (2020) Microplastic pollution in a stormwater floating treatment wetland: detection of tyre particles in sediment. Sci Total Environ 713:136356