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Microplastics and nanoplastics in stormwater management engineered porous media systems: a systematic review of their sources, transport, retention, and removal characteristics

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The widespread presence of microplastics and nanoplastics (MNPs) in stormwater poses significant risks to both ecological and human health, necessitating the development of effective and sustainable mitigation strategies. Stormwater management engineered porous media systems (SWMEPMS) have emerged as promising solutions, leveraging filtration processes to capture and retain MNPs while supporting Sustainable Development Goals (SDGs 6, 11, and 14). Despite their potential, research on the fate of MNPs within SWMEPMS remains limited. Most importantly, no prior study has systematically and comprehensively reviewed how SWMEPMS remove MNPs from stormwater, particularly in relation to removal mechanisms, porous media and MNP characteristics, and water chemistry, despite their growing application and relevance. To bridge this gap, the standardized PRISMA methodology was employed to review the sources, transport, retention, and removal characteristics of MNPs in SWMEPMS. Key findings of the review highlight that MNPs in stormwater runoff are predominantly composed of polymers, including polyethylene, polypropylene, polystyrene, and tire wear particles (TWPs). SWMEPMS demonstrate up to 100% removal efficiency through mechanisms like sedimentation, straining, entrapment, entanglement, accumulation, agglomeration, electrostatic interactions, and surface complexation. Engineered porous media characteristics, such as surface properties, particle size distribution, and porosity, play crucial roles in enhancing removal efficiency, with porous media like limestone and biochar demonstrating greater performance than sand. The presence of functional groups, such as carbonyl, hydroxyl, carboxyl, and amino groups, on either the media or MNPs enhanced the removal efficiency of SWMEPMS. This review synthesizes existing knowledge, identifies gaps, and offers recommendations for future research to enhance this technology.

Environmental significance

Plastic particle pollution, particularly microplastics and nanoplastics (MNPs), poses an escalating threat to aquatic ecosystems and human health, especially *via* stormwater runoff. This review addresses a critical gap by exploring how stormwater management engineered porous media systems (SWMEPMS) reduce MNP pollution. By systematically and critically synthesizing knowledge on MNP sources, transport, retention, and removal characteristics within SWMEPMS, the key findings include identifying the primary removal mechanisms of MNPs and demonstrating that SWMEPMS can achieve up to 100% removal efficiency. The findings support sustainable water treatment practices and emphasize the need for more effective green infrastructure to protect stormwater quality. This work provides evidence and strategies to guide future research and policymaking toward resilient, low-cost stormwater treatment solutions in urban environments.

1 Introduction

Plastics are a subgroup of organic polymers consisting of repeating monomers and various additives, which give them a wide range of chemical compositions and physical properties.[1] As plastics break down into varying sizes due to chemical and/or physical processes, residual monomers and unbound additives may be released, potentially exhibiting hazardous properties that can affect the environment and its compartments. Discovered by a Belgian Chemist, Leo Baekeland, in 1907,[2] plastic was considered, and arguably remains, a revolutionary chemical substance. Despite numerous studies conducted on plastic pollution over the past decade, it continues to pose a significant challenge to the three pillars of sustainability (*i.e.*, environmental, social, and economic

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systems).[3,4] Plastic particles have been ubiquitous since the 1970s, and they continue to emerge as a contaminant of concern, prompting increasing attention from experts and organizations due to their significant threat to ecosystems.[5,6] Studies have indicated that plastic particles have demonstrated a severe threat to both human and ecosystem health, and predictions suggest that, if current trends continue, the concentration of plastic particles in natural environments could double by 2030.[7] This issue has been exacerbated by the increased use of plastic-based personal protective equipment (PPE), such as gloves and facemasks, during the COVID-19 pandemic;[8] a practice that has contributed to heightened plastic waste. Consequently, without a holistic approach to managing plastic wastes, the prediction may not just come to pass but be aggravated, thereby increasing the amount of plastic pollution in the atmosphere, lands (and therefore stormwater runoff), and receiving water bodies, posing threats to terrestrial and aquatic life. While some researchers initially argued that the concentrations of plastic particles were too low to harm human health, more recent studies have detected microplastics and/or nanoplastics in several human bodily fluids and organs.[9–19]

Although research into plastic particles in the oceans was first noted in literature in the 1970s,[20] the term microplastics (MPs) was coined by Thompson *et al.* in 2004 in their study to present evidence that MPs were prevalent in oceans and sedimentary habitats.[21] They posited that these pollutants could adsorb, release, and transport chemicals. On the other hand, initially, nanoplastics (NPs) were hailed as "intelligent materials" by Guiness in 1995, a term introduced with the vision of transforming product design to make daily items more interactive and versatile.[22] However, over twenty years later, it has become clear these same particles have emerged as pollutants, posing serious threats to both living organisms and ecosystems, necessitating immediate and significant attention.[23] For example, NPs have been demonstrated to increase the leaching rate of metalloids, such as arsenic, on land by five times.[24]

MPs and NPs are most commonly described as plastic particles with the longest dimension between <5000 μm and 1–100 nm, respectively.[25,26] However, it is important to note that no consensus has been reached regarding their size definitions, particularly with respect to the lower boundary for MPs and the upper boundary for NPs.[27,28] For example, some studies describe MPs and NPs as spanning 1–5000 μm and 1–100 nm,[28,29] 1–5000 μm and 1–1000 nm,[28,30] or 0.1–5000 μm and 1–100 nm,[31,32] respectively, thus creating ambiguity. This inconsistency either leaves a gap in NP analytics for particles between 100 nm and 1 μm or fuels debate over whether 1 μm

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and/or 100 nm should be classified as MPs or NPs. The absence of a unified definition in the literature creates inconsistencies across public policy, legislation, and research, further complicating existing efforts to monitor and mitigate the impacts of MPs and NPs in the environment. To ensure consistency with the studies reviewed in this paper, MPs and NPs are here defined as plastic particles measuring >0.1–5000 μm and 1–100 nm, respectively. In addition, the acronym "MNPs" is used throughout this work to collectively denote MPs and NPs, ensuring clarity and conciseness.[33,34]

Due to accelerated anthropogenic activities, urban stormwater runoff has increasingly been recognized as a major pathway for the transport of MNPs into receiving water bodies, especially NPs, which can easily pass through stormwater control measures (SCMs), partly because they remain uniformly suspended in water over long durations.[35] Stormwater runoff is a cocktail of precipitation and other contaminants, such as metals, metalloids, oil and grease, organic matter, pesticides, nutrients, and other chemicals (*e.g.*, per- and polyfluoroalkyl substances (PFASs)). Several studies have demonstrated MNPs as facilitators for the transport of these other contaminants. For example, MPs such as tire wear particles, polyethylene, polystyrene, polyamide, and polypropylene are good adsorbents for metals such as iron, manganese, zinc, copper, cadmium, and/or nickel,[36,37] and these MP polymers are known to be dominant in stormwater runoff.[38–40] Similarly, Pokhrel *et al.* found that polystyrene, polypropylene, and polyethylene terephthalate-based NPs generated from real-world plastic wastes adsorb metals such as manganese, cobalt, zinc, cadmium, and lead, with almost 99% of lead adsorbed within five minutes.[41]

Beyond metals and metalloids, MNPs have also been shown to act as carriers of hydrophobic organic pollutants and other co-contaminants. Tanaka and Tanaka reported that polyethylene adsorbs more hydrophobic chemicals, such as polychlorinated biphenyls (PCBs), than other polymers,[42] while Koelmans *et al.* reported that environmental pollutants with higher fugacity than plastic would be adsorbed by MPs until the net concentration of the contaminants on the MPs remains constant.[43] Shan *et al.* observed that crude oil showed a strong affinity for polyethylene MPs and could reach equilibrium within five minutes.[44] Xue *et al.* suggested that MPs made of thermoplastic polyurethane could create complex pollution scenarios by simultaneously attracting antibiotics in addition to metals,[45] while a study by Rubin *et al.* indicated that contaminants bound to the surfaces of MPs could see their toxicity increased tenfold.[46,47] In addition, Mukonza and Chaukura reported that MPs can act as carriers of PFASs through multiple physico-chemical sorption processes, including π-interactions, cation exchange, electrostatic forces, hydrogen and halogen bonding, and hydrophobic interactions. These interactions enhance the persistence and mobility of PFASs, contributing to their detection even in remote environments such as the Arctic.[48] Collectively, these findings highlight the dual role of MNPs not only as pollutants themselves but also as transport agents for co-contaminants, thereby compounding their environmental risk. Despite this growing evidence, conventional stormwater management systems are often ineffective at capturing or retaining MNPs.[49] Their design limitations, such as the absence of engineered porous media and short hydraulic retention times, allow MNPs to pass through them and enter receiving waters, underscoring the need for stormwater management approaches that incorporate engineered porous media.

Among various mitigation strategies, stormwater management engineered porous media systems (SWMEPMS) have emerged as promising tools for controlling MNP pollution in stormwater and urban runoff. Here, we defined SWMEPMS as non-vegetated systems that predominantly utilize engineered porous media to mimic natural drainage regimes through the infiltration, storage, percolation, and evapotranspiration of stormwater and urban runoff. The ultimate advantage of these SWMEPMS is their adherence to filtration theory, which underpins their development as a relatively "green" water treatment technology.[50] Further, engineered porous media is defined as a material that has been designed or selected for specific structural or functional properties, including porosity, permeability, and surface characteristics, to facilitate the movement and treatment of stormwater. SWMEPMS are part of the family of "green" stormwater management practices,[50] that are generally referred to as sustainable urban drainage systems or sustainable drainage systems (SuDS) in the United Kingdom and many parts of Europe, low impact development (LID) in North America and New Zealand, water sensitive urban design (WSUD) in Australia, and sponge city in China.[51,52] Although many would have preferred a unified terminology, we still cannot ignore the fact that terminologies represent local content in knowledge and understanding.[53,54] All SWMEPMS are considered to be LID; however, not all LIDs are SWMEPMS. Therefore, the SWMEPMS considered in this review are identified in the subsequent section with a short description of what they are.

Generally, SWMEPMS, like most LID technologies, have unique properties and advantages that support several of the UN Sustainable Development Goals (SDGs), including:[53] (1) removal and treatment of stormwater pollutants, such as oil and grease, metals, and metalloids (SDGs 6 and 14), (2) use of local and/or recycled products, thereby improving local economy (SDGs 8 and 12), (3) simple to construct while providing resilient stormwater infrastructure and efficient stormwater management (SDGs 9 and 11), (4) multi-stage and multipurpose drainage systems as most of them can be used during initial road construction for surface and/or subsurface water management as well as contributing to urban aesthetics, enhancing the visual appeal of public spaces (SDG 11), (5) possessing high hydrologic performance, thereby providing rapid control and management of stormwater (SDGs 11 and 13), (6) low cost and high carbon footprint savings, thereby promoting environmental sustainability (SDGs 12 and 13).

Plastic particles such as microbeads are banned in some countries, including the United Kingdom, the USA (California), Canada, and New Zealand.[55] These bans resulted from extensive studies over the past decade on the negative impacts of plastic particles on the environment. However, as previously stated, despite these regulations, the complexity of plastic particles, especially when considering the several sources of plastic particles, necessitates a holistic approach to addressing their environmental impacts, particularly within stormwater runoff and management systems like SWMEPMS. This is why the study of plastic particle availability and fate in stormwater runoff and stormwater management structures, such as SWMEPMS, requires more attention. For example, plastic particles are assumed to be treated by some SWMEPMS, such as infiltration trenches, highway filter drains, *etc.*, before reaching the outfall or receiving water body. Nevertheless, there is no certainty in this concept as studies of plastic particle migration and removal characteristics in most types of stormwater management structures are largely understudied and remain an emerging area of research.[56–58] Moreover, much of the existing research has been centred on the impacts of plastic particle pollution on the downstream, particularly their accumulation and effects in rivers and oceans. While such research is crucial, it is equally important to understand what is happening upstream. In fact, to the best of our knowledge, there is no published systematic review that synthesizes and critically analyzes the prevalence and fate of MNPs in SWMEPMS, considering their sources, transport, retention, and removal characteristics.

Although some recent reviews have attempted to address parts of this knowledge gap,[59–63] they typically fall short in several critical ways. Specifically, they often exclude NPs entirely, thereby overlooking their unique behavior, toxicity profile, and increasing prevalence in stormwater runoff. They also lack focused evaluation of engineered porous media systems as a distinct subcategory within green infrastructure, despite their growing application and promising filtration potential. Moreover, these reviews do not employ a standardized methodology such as the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method, which is essential for ensuring transparency, reproducibility, and methodological rigor in review-based research. Additionally, they fail to critically analyze the multiple removal mechanisms that govern the retention and removal of plastic particles in stormwater management facilities. Finally, they neglect to contextualize plastic particle pollution within a broader coupled-systems framework, limiting understanding of how MNP pollution interacts with and impacts the three pillars of sustainability (*i.e.*, environmental, social, and economic systems). Therefore, this paper aims to fill these critical gaps by conducting a systematic and critical review of MNP prevalence and fate in SWMEPM, focusing on their sources, transport, retention, and removal characteristics, using the standardized PRISMA methodology.

2 Methodology

This study employed the PRISMA methodology, an internationally recognized and validated framework for conducting systematic reviews.[64] It is recognised for enhancing the clarity, rigor, transparency, and reproducibility of systematic reviews.[65,66] The subsequent sections outline the application of this method in achieving the objectives of this study. Furthermore, for clarity, we categorized the SWMEPMS reported in this study based on their structural characteristics and functions, as shown in Table 1. We generated the list in Table 1 based on our knowledge of LID technologies as well as the existing literature.[59,67]

2.1 Protocol

The review was conducted by systematically searching for peer-reviewed articles that address MNPs in stormwater within SWMEPMS, focusing on their sources, transport, retention, and removal characteristics.

2.2 Eligibility criteria

The criteria for selecting eligible studies for this review were as follows: (1) the studies must be peer-reviewed original research articles containing primary data, whether qualitative or quantitative; (2) the study must investigate MNP removal by SWMEPMS; while NP removal studies not strictly in the context of stormwater management were added, they were deemed relevant since the experimental setups, including the NP polymers used and the findings, are closely aligned with those applicable to trench-based SWMEPMs for stormwater treatment; (3) no restrictions were placed on the geographic locations or the periods during which the studies were conducted; and (4) all included studies must be published in English to ensure consistency and clarity in data analysis. Studies were excluded if they met any of the following non-eligibility criteria: (1) secondary research such as review papers, editorials, opinion pieces, and conference proceedings and (2) studies that do not provide sufficient detail or extractable data on the investigation of MNP sources, transport, and/or removal characteristics using SWMEPMS.

2.3 Information sources

The primary databases utilized for this systematic review were Engineering Village, Web of Science (WoS), and Scopus. These databases were chosen as they capture the breadth and depth of engineering literature related to MNPs in SWMEPMS and are promptly and consistently updated to reflect new research publications[69,70] Moreover, they are noted for their systematic organization and transparent operation.[69,71] Other large databases, such as Google Scholar, were omitted from this study due to lack of comprehensive citation data and inconsistency.[72]

2.4 Search strategy

The initial literature search was conducted on the 29th of April 2024 and finalized on the 22nd of April 2025. The search syntaxes used to retrieve relevant papers from the databases are shown in Table 2. For Engineering Village, searches encompassed all its host databases, including Compendex, Inspec, GeoRef, and GEOBASE. In WoS, searches covered all available

Table 1 Classification of SWMEPMS

SWMEPMS class	Structural characteristics and functions	List of SWMEPMS
Pavement-based SWMEPMS	Primarily hard, permeable surfaces designed to allow stormwater to permeate, reducing runoff and promoting storage and infiltration. These surfaces are typically porous, permeable, or pervious in nature	Porous/permeable/pervious asphalt Porous/permeable/pervious concrete Permeable interlocking concrete pavers (PICP) Porous/permeable/pervious pavers
Trench-based SWMEPMS	Excavated trenches, wells, or basins filled with porous materials designed to capture and filter stormwater. Some are engineered for infiltration, while others may be designed for stormwater capture, filtration, and runoff conveyance only. Notably, highway filter drains are typically engineered primarily for draining, filtration, and conveyance of stormwater, rather than infiltration into native soils, which distinguishes them from infiltration trenches[68]	Infiltration trenches Highway filter drains (HFDs) Edge drains Sand filters Dry wells Soakaways Biofilters

fields. However, for Scopus, searches were limited to selected fields, specifically the title, abstract, and keywords. This approach was adopted for Scopus because including all fields would also cover articles cited in the reference lists of papers within its database.[73]

Here (Table 2), we acknowledge the extensive array of terminologies associated with each of the SWMEPMS to ensure a comprehensive search. For example, the term 'permeable pavement' is synonymous with 'porous pavement' and 'pervious pavement'. Recognizing and incorporating these synonymous terms in our search syntax was imperative to capture the diverse nomenclature and to retrieve all relevant studies pertaining to the categorized SWMEPMS. We believe we have included all the SWMEPMS that are currently relevant to stormwater management practices and our research. However, we acknowledge the potential existence of other SWMEPMS that may not be applicable to this study, possibly due to constraints such as the availability of literature, inconsistencies, or ambiguities in terminology usage.

2.5 Study selection

The selection process we followed to screen and confirm the eligible papers from the search results included the collation of all the extracted papers from databases. During the process of duplicate removal, Engineering Village was prioritized, with Compendex selected as the preferred database among its four hosted databases, followed by Web of Science. The first author primarily handled the extraction and screening of relevant articles under the supervision and review of the co-authors. The entire research team subsequently engaged in a collaborative review and analysis of the included studies, ensuring a thorough synthesis, critical, and comprehensive review of the literature.

3 Results and discussion

3.1 Eligible literature trend and bibliometric analysis

This section presents and discusses the results obtained using the methodology described in the previous section. Fig. 1 shows

Table 2 Search syntax strategies and the number of extracted papers per database prior to the comprehensive application of the eligibility criteria

SWMEPMS classification	Search syntax
Pavement-based SWMEPMS	("Plastic particle*" OR microplastic* OR "micro-plastics*" OR nanoplastic* OR "nano-plastic*") AND ("porous asphalt*" OR "permeable asphalt*" OR "pervious asphalt*" OR "porous pavement*" OR "permeable pavement*" OR "pervious pavement*" OR "porous concrete*" OR "permeable concrete*" OR "pervious concrete*" OR "permeable interlocking concrete paver*" OR "porous paver*" OR "permeable paver*" OR "pervious paver*")
Trench-based SWMEPMS	("Plastic particle*" OR microplastic* OR "micro-plastics*" OR nanoplastic* OR "nano-plastic*") AND ("infiltration well*" OR "infiltration pond*" OR "infiltration basin*" OR "infiltration cell*" OR "infiltration chamber*" OR "infiltration trench" OR "edge drain*" OR "infiltration trenches" OR "filter drain*" OR "highway filter drain*" OR "sand filter*" OR "sand-filter*" OR "dry well*" OR "dry-well*" OR soakaway* OR "soak-way*" OR biofilter* OR "bio-filter*")

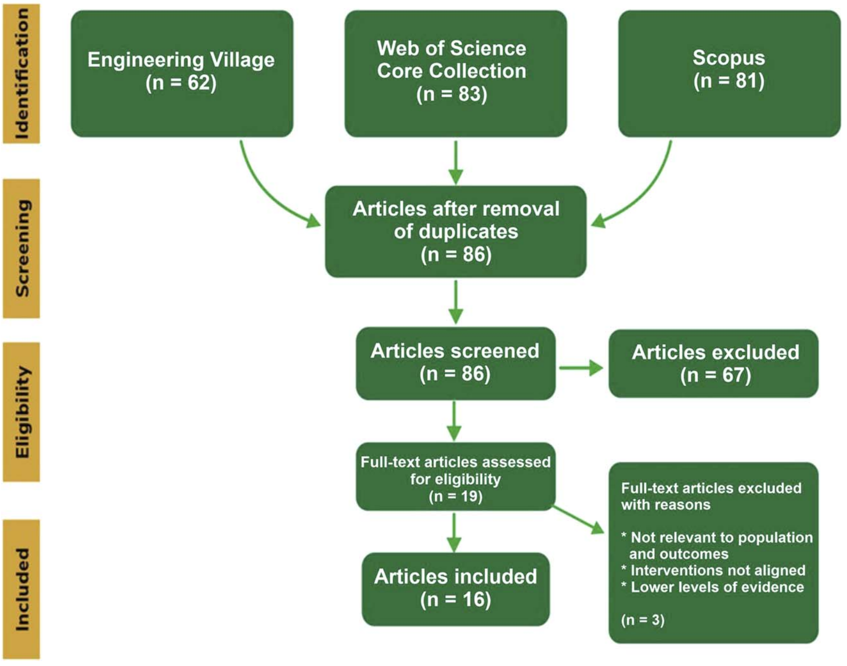

Fig. 1 PRISMA flowchart of article selection from the databases: extraction, duplication removal, and screening.

the PRISMA flow chart, detailing the number of publications extracted from each of the databases, duplicates removed, and the eligible articles after the screening. The figure shows that a total of 226 papers were extracted from the databases (Table 2). Nineteen research articles were preliminary eligible after screening the articles by reading the titles and abstracts. However, upon reviewing the full texts, only 16 papers fully met the eligible criteria as stated in Section 2.2, resulting in the removal of three additional papers, mainly due to the articles lacking focus on MNP removal using SWEMPM. In summary, a total of six papers studied MNP removal using pavement-based SWMEPMS, and ten papers studied MNP removal using trench-based SWMEPMS.

Key parameters extracted from the eligible research articles included publication year and characteristics of experimental setups. These parameters were crucial for conducting analyses, including trend analysis and bibliometric assessments. Analyzing publication trends provides insights into the evolution of research themes, highlighting shifts in scientific focus and priorities within the scientific community. Fig. 2 illustrates

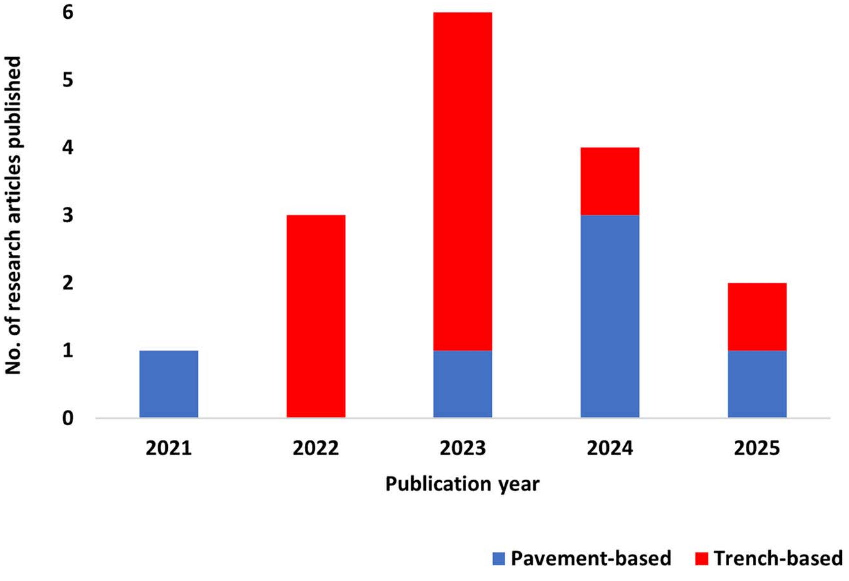

Fig. 2 Trends in scholarly publications on the removal of MNPs using SWEMPMS.

the temporal distribution of the eligible studies, underscoring the use or potential use of SWMEPMS for the removal of MNPs from stormwater runoff. The figure indicates that primary research on the removal of MNPs by SWMEPMS represents a nascent field of study, with the earliest study published in 2021. This emergence is expected, given that the term "MPs" was first introduced in 2004, as mentioned in the Introduction section, and studies of the removal of plastic particles by LID technologies are still developing. Notably, the first pavement-based SWMEPMS article (1) was published in 2021, and the first trench-based SWMEPMS articles (3) were published in 2022. In 2023, trench-based articles (5) outnumbered pavement-based (1), and in 2024, pavement-based articles (3) outnumbered trench-based articles (1). In 2025, only one study has been published for each SWMEPMS type thus far. Generally, while interest in the field appears to have grown sharply between 2021 and 2023, the number of publications declined in 2024, with only two studies published so far in 2025. This fluctuation may simply reflect the early stage of research activity in this area rather than a consistent trend.

To further analyze the dataset, we utilize VOSviewer software to conduct a focused bibliometric analysis based on keyword co-occurrence. This technique involves overlay visualization, which identifies patterns and relationships among frequently occurring keywords. By extracting and visualizing these relationships, we aimed to reveal underlying patterns and trends that were not readily visible in the previous bibliometric analysis. The resulting network graph displays nodes representing the keywords, while the links depict their co-occurrence, highlighting the most frequently associated terms and their connections. This analysis is essential for identifying dominant themes and tracking the development of research topics, thus providing valuable insights into the prevailing scientific themes surrounding research on MNP removal using SWMEPMS. This method enables a deeper understanding of the field's conceptual structure and evolving trends. The keyword co-occurrence map, generated from RIS-formatted bibliographic data extracted from Engineering Village databases (with Compendex used as the preferred source in cases of duplicates) using the search syntax shown in Box 1, is presented in Fig. 3. The analysis utilized a complete count of keyword co-occurrences, setting a threshold where each keyword must appear at least three times. The dataset contained 230 keywords, of which 30 met the established threshold. However, nine keywords were manually removed due to their lack of direct relevance to the context of our study. Rainbow was selected as the color of the overlay visualization under predefined colors, while all other parameters were kept at their default settings.

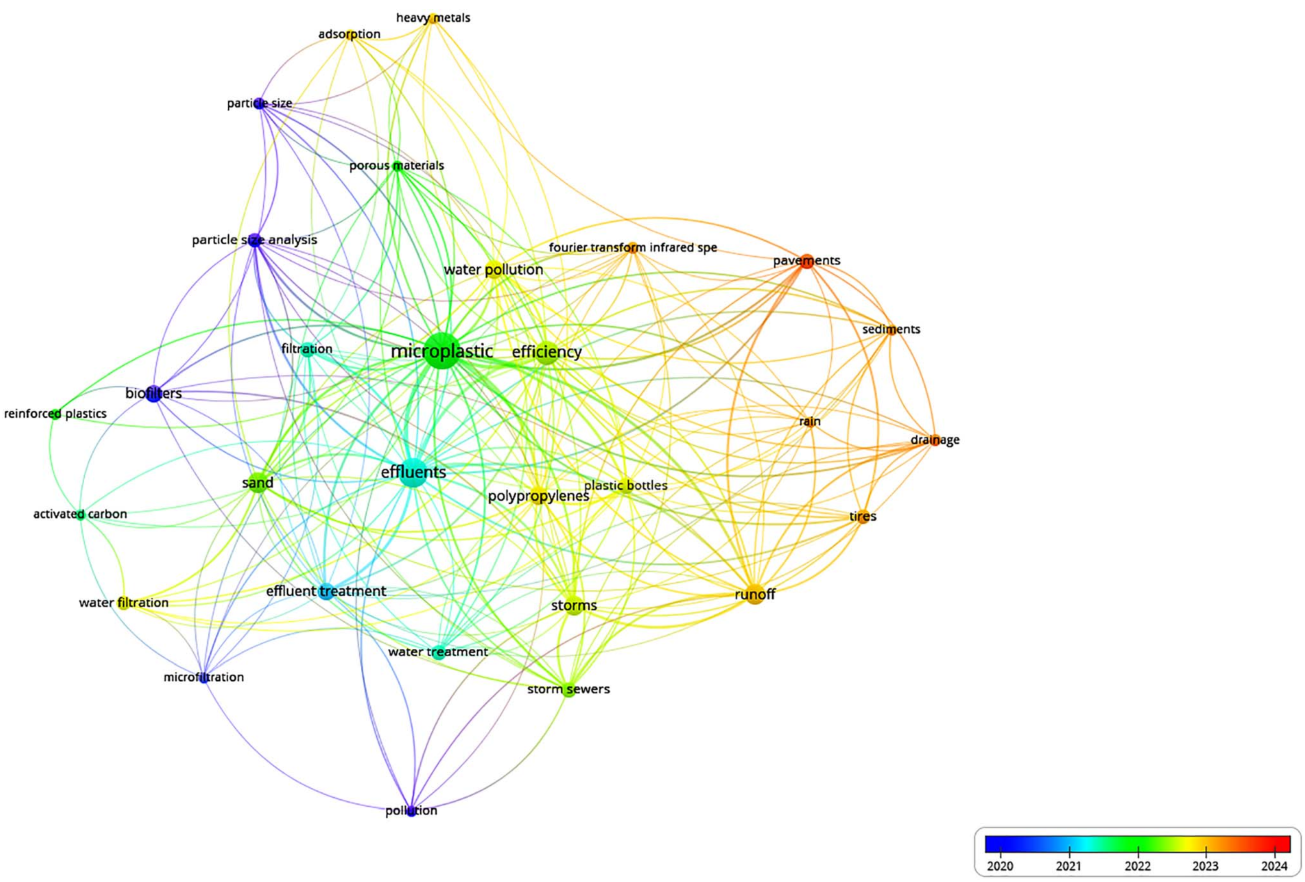

Fig. 3 Overlay visualization bibliometric analysis of research on MNP removal using SWMEPMS. Thirty keywords were grouped into five clusters. This resulted in 217 links and a total link strength of 488.

Box 1 search syntax for the VOSviewer

("plastic particle*" OR microplastic* OR "micro-plastics*" OR nanoplastic* OR "nano-plastic*") AND ("porous asphalt*" OR "permeable asphalt*" OR "pervious asphalt*" OR "porous pavement*" OR "permeable pavement*" OR "pervious pavement*" OR "porous concrete*" OR "permeable concrete*" OR "pervious concrete*" OR "Permeable Interlocking Concrete Paver*" OR "porous paver*" OR "permeable paver*" OR "pervious paver*" OR "infiltration well*" OR "infiltration pond*" OR "infiltration basin*" OR "infiltration cell*" OR "infiltration chamber*" OR "infiltration trench" OR "infiltration trenches" OR "filter drain*" OR "highway filter drain*" OR "sand filter*" OR "sand-filter*" OR "dry well*" OR "dry-well*" OR soakaway* OR "soak-way*" OR biofilter* OR "bio-filter*")

Using the syntax in Box 1, 300 records were extracted from the four databases within the Engineering Village search engine.

The network in Fig. 3 illustrates a comprehensive mapping of research topics around MNPs and SWMEPMS. The size of each node indicates the frequency of the keyword's occurrence in the dataset, with larger nodes suggesting higher frequency.[74] The lines connecting the nodes represent the co-occurrence of keywords in the same papers.[74] A thicker line implies a stronger association between the keywords, indicating that they frequently appear together in the literature.[74] The distance between two nodes generally represents the relatedness or similarity between the keywords; nodes that are closer together are more strongly related, often because they co-occur more frequently within the same set of papers. The arrangement of nodes into clusters indicates that these keywords have been frequently studied together across multiple publications.[74] The gradient from blue to red along the timeline starting from 2020 indicates the recency of the topics, with warmer colors representing recent discussions. The network shows strong interconnections among topics related to pollution management, filtration efficiency, and stormwater-related pathways, as well as associated analytical methodologies. This visualization helps in identifying key areas of current research and potential gaps that might require further investigation, such as specific impacts on health, filtration or removal mechanisms, and/or more research in NPs, which is not represented at all in the network. Notably, the keyword 'stormwater' does not appear in the network, reinforcing our observation that research on the removal of MNPs by SWMEPMS has only recently begun to emerge.

3.2 Classification and sources of MNPs

MNP sources are categorized into primary and secondary.[75,76] Primary sources are manufactured directly (*e.g.*, microbeads) and typically enter ecosystems through discharge from industry and households or accidental spills, while secondary sources arise from the breakdown of larger plastics by mechanical processes, UV radiation, or microbiological activity.[75,76] Trends in studies conducted across different regions, including the USA, Italy, Germany, Japan, and China, show that secondary-sourced MNPs represent one of the highest contributors to MNP pollution.[6] This aligns with the findings of Karthik *et al.*, who found fragment-type particles, which are secondary-sourced, constituted 47–50% of the total MPs along the south-east coast of India.[77] Indeed, the MNPs used in some of the studies reviewed in this work, as shown in Table 3, were from residential and commercial sources.

MNP morphology, commonly defined as the appearance (*i.e.*, form and shape)[78–80] and sometimes including color, along with particle size and polymer type, impact their fate in the environment and removal by engineered treatment systems (*e.g.*, retention in porous media). Thus, knowledge of MNP classification is crucial for developing effective mitigation and treatment strategies. Table 3 presents MNP classification and source information for the MNPs used in the experiments in the reviewed research articles and shows the frequency of characterized MNPs based on the number of references. For example, fragment-form MNPs were the most used in the reviewed studies, while powder-MNPs were the least used.[81] Interestingly, Rullander *et al.*[39] found significant discrepancies between the advertised average size of commercially purchased MPs and the actual sizes observed using advanced imaging techniques. This discrepancy underscores the need for in-house verification of particle properties in scientific studies to ensure accuracy and reliability.

This classification highlights the diversity of MNPs examined across different experiments. It emphasizes the various physical and chemical properties, such as shapes (*e.g.*, spherical, angular, elongated, irregular), colors (*e.g.*, green, black, blue), polymer types (*e.g.*, PS, PE, PP, EVA, EPDM rubber), and sources (*e.g.*, commercially purchased, residential, industrial, highway runoff). This diversity is crucial for studying and understanding the retention capacity of MNPs in SWMEPMS. The "–" symbol indicates missing information or data not listed, either because the experiment was not conducted or the data was not explicitly reported.

3.2.1 MNPs in stormwater runoff. The rapid increase in urbanization and industrialization has resulted in significantly expanded road networks and a larger fraction of impervious areas, increasing volumes and flow rates of stormwater runoff.[88] Stormwater runoff is a multifaceted blend of precipitation, suspended sediments, natural and human-made debris, and chemical contaminants.[6] In fact, stormwater runoff is estimated to contribute approximately 5–10% of the total plastic influx into the global oceans.[54,81] New findings indicate that MNPs can be highly toxic in aquatic ecosystems at low concentrations. For example, Mitchell and Jayakaran reported that urban streams in the Pacific Northwest of the USA are experiencing a phenomenon in which coho salmon die in large numbers before spawning.[81,93] This issue, Urban Stream Mortality Syndrome (URMS), is linked to 6PPD-quinone (6PPDQ), used in vehicle tires to protect against ozone damage. As tires wear, the resulting MNPs, known as tire wear particles (TWPs), contain 6PPDQ, released as they break down.

Table 3 Classification of MNPs by form, shape, color, polymer type, and source

MNP forms	MNP classes	Shapes	Colors	Density (g cm^{-3})	Polymer types	Sources
Bead[39,82,83]	NPs[82] and MPs[39,83]	Spherical[39,82,83]	Green[83] and blue[83]	1.02,[39] 0.94,[39] 1.05,[83] and 1.35 (ref. 83)	Polystyrene (PS),[82,83] polyamide,[39] polyethylene (PE),[39] and polyethylene terephthalate (PET)[83]	Commercially purchased[39,82,83] and custom manufactured[39]
Fragment[6,39,54,81,83–89]	MPs[6,39,54,81,84–89]	Spherical,[81] angular,[54] elongated,[39] and irregular[84–86]	Black[81,89] and red[83]	1.20,[81] 0.90,[39] < 1.6,[84,86] 0.92,[85] 1.02,[85] 1.35 (ref. 85) and 1.03 (ref. 83)	PE,[6,85,88] polypropylene (PP),[6,39,54,83,85–87] tire wear particles (styrene butadiene rubber),[81,89] ethylene-vinyl acetate (EVA),[87] ethylene propylene diene monomer rubber (EPDM rubber),[87] PET,[84,85] and PS[85]	Residential area,[6,54,89] commercially purchased,[81,83] industrial area,[89] commercial area,[54,89] custom manufactured[39,84–86] and highway runoff[87]
Fiber[6,39,54,84–87]	MPs[6,39,54,84–87]	Elongated,[39] irregular[84–86]	—	1.35,[39] < 1.6,[84,86] 0.92,[85] 1.02,[85] and 1.35 (ref. 85)	PET,[6,39,84,85] PP,[39,54,85–87] EVA,[87] EPDM rubber,[87] and PS[85]	Residential area,[6] industrial area,[89] commercial area,[54] custom manufactured,[39,84–86] and highway runoff[87]
Film[6,54]	MPs[6,54]	—	—	—	PE[6] and PP[6,54]	Residential area[6] and commercial area[54]
Pellet[90,91]	MPs[90,91]	—	—	0.95 (ref. 91)	PE[90,91] and nylon[90]	Commercially purchased[90,91]
Powder[83,91,92]	MPs[83,91,92]	—	White[83]	1.17,[91] 0.00094,[92] 0.0014,[92] and 1.37 (ref. 83)	Tire powder,[91] PE,[92] and PET[83,92]	Commercially purchased[83,92]

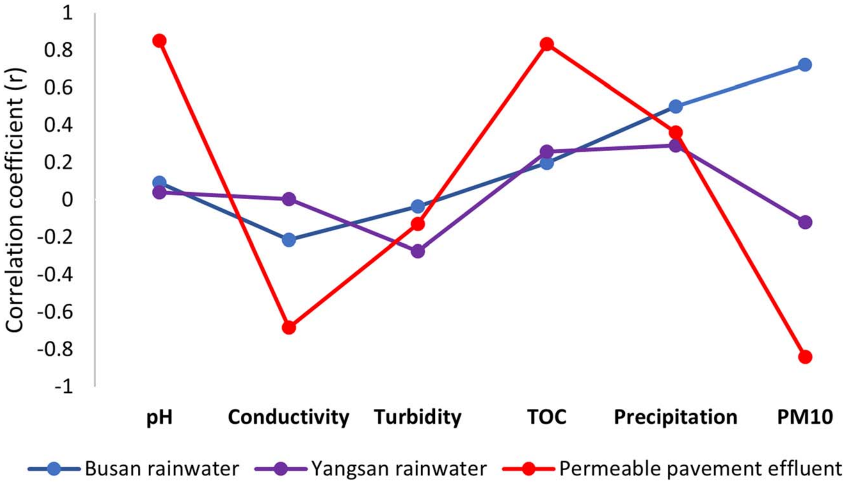

Fig. 4 Correlation coefficients of MPs with various water quality parameters (designed by the authors of this present work using the data reported by Kong *et al.*).[6] Rainwater samples were collected from Busan, Korea, and Yangsan, Korea, representing commercial and residential urban settings, respectively. Effluent from a pavement-based SWMEPMS in Yangsan was also sampled.

Other common MNP polymers found in stormwater include PP, PE, and PS.[81,88,89] However, TWPs accounts for more than 30% of the total MNPs released into the environment, with per capita discharges estimated between 0.2 and 5.5 kg per year,81,89 and thus contribute a significant fraction of the total MNPs in stormwater. Furthermore, the experiment conducted by García-Haba *et al.* stated that TWPs accounted for 40% of MPs found in the stormwater in an urban catchment.[54] Another study reported by Rasmussen *et al.* found that among the aforementioned common plastic polymers found in stormwater, styrene-butadiene rubber (SBR), which is one of the primary components of TWPs, was the most prevalent polymer detected in runoff and sediment samples.[89] The two main issues with TWPs are that: (1) they are ubiquitous, a source of several harmful chemicals, and come in a broad range of sizes and morphologies; hence, their distribution, transport, and fate become complex,[81] and (2) they often degrade on road pavements due to mechanical actions supported by UV rays, thereby easily combining with road dust and other materials to create agglomerates otherwise known as tire and road wear particles (TRWP).[81,89]

The abundance of MPs in stormwater is notably higher compared to effluents from wastewater treatment plants.[6] This underscores the significant role of stormwater as a major contributor to MNP pollution. This is likely due to the fact that stormwater runs off directly from urban surfaces, often bypassing natural filtration processes, and is exacerbated by extensive impervious surfaces from urbanization and industrialization. MP levels in stormwater runoff vary significantly, ranging from 2.00 to 110.59 MP L^{-1}, with some studies reporting even broader variations from <1.00 to 8550 MP L^{-1} due to differences in catchment characteristics and rainfall intensities.[59] This variability indicates the complexity of comparing MP data across different studies and the influence of localized factors, such as land use land cover (LULC), rainfall intensity and duration, and methodological procedures.[59]

Current limitations in MNP identification, particularly for complex plastic polymer types like TWPs, hinder the ability to fully understand the composition and potential toxicity of MNPs in stormwater. To address these challenges, developing standardized sampling and analytical methods for MNPs in stormwater can improve the comparability and reliability of data. Additionally, combining MNP monitoring with conventional stormwater quality parameters could enhance the predictive capabilities for MNP pollution in our environment. Kong *et al.* found a strong correlation between the number of MPs and various rainwater quality indicators (*i.e.*, pH, conductivity, turbidity, total organic carbon (TOC), precipitation, and PM10), suggesting that monitoring stormwater quality could serve as an indirect method for estimating MP pollution levels.[6] Fig. 4 shows the correlation coefficients (r) between the number of MPs and the various physico-chemical parameters based on the data reported by Kong *et al.*[6] The stormwater employed by Kong *et al.* represents commercial and residential catchments. Additionally, effluent from a permeable pavement SWMEPMS was employed. The differences in correlation coefficients across the three stormwaters demonstrate how location, LULC, and treatment impact the relationship between MPs and water quality parameters. For instance, the pavement-based SWMEPMS exhibits a strong positive correlation with pH and TOC while showing a strong negative correlation with PM10, which could be due to the removal mechanisms within the pavement-based SWMEPMS that target PM10 more efficiently than MPs. In contrast, Busan rainwater has moderate to strong positive correlations with precipitation and PM10, and Yangsan rainwater generally shows negligible to weak correlations. Given that the pH of pavement-based SWMEPMS effluents was strongly correlated with precipitation and increased as the water passed through the pavement due to the composition of the SWMEPMS,[6] we hypothesized that the initial lower pH levels of acid rain before neutralization by the permeable pavement may have accelerated the breakdown of organic materials. This

Table 4 MNP quantification methods, technology, and summary of analysis[a]

MNP quantification methods	Technology	Instruments	Representative summary of analysis	Advantages	Disadvantages
Physical	Microscopy[54]	Stereomicroscope[54]	Filtered MPs were visually analyzed to identify and count MPs[54]	(1) High-resolution imaging allows direct visualization and identification of MNPs; and (2) can provide morphological details such as shape and surface texture	(1) Time-consuming; (2) may require trained personnel; (3) may miss NPs because of their particle size; and (4) does not provide chemical composition or polymer-specific information
	Gravimetric[88,91]	Analytical balance[91]	MPs were quantified by filtering, drying, and weighing samples to determine net mass[88,91]	(1) Simple and cost-effective for quantifying mass changes; (2) no advanced instrumentation or expertise is required; and (3) provides bulk mass estimates for samples	(1) May not be suitable for NPs; and (2) cannot be used for MNP qualification analysis
Chemical	Spectroscopy[6,39,82,83,92,98]	Micro-Fourier transform infrared spectrophotometer (μ FTIR),[6,39,87,92] ultraviolet spectrophotometer,[98] fluorescence spectrophotometer[82,83]	FTIR quantified MPs within wavenumber ranges of 1300–4000 and 3750–950 cm^{-1}.[6,39] Ultraviolet spectrophotometry measured NP concentrations at 200 nm.[98] Fluorescence spectroscopy determined NP concentrations at excitation/emission wavelengths of 488/518 nm[82]	(1) Spectroscopy techniques (like FTIR or Raman spectroscopy) provide detailed chemical information, including polymer type and functional group identification; (2) non-destructive, preserving samples for further analysis; and (3) spectroscopy techniques (like FTIR or Raman spectroscopy) can detect subtle differences in polymer composition across different particles	(1) Expensive instrumentation and maintenance costs; (2) requires technical expertise for both operation and data interpretation; and (3) detection limits may vary depending on the polymer type and functional group abundance—for example, FTIR and Raman are generally unsuitable for detecting NPs, and FTIR may not effectively detect smaller MPs (<10–20 μm)
	Wet chemistry[90]	Titration apparatus[90]	MP concentrations were determined using a modified chromic acid wet oxidation method, with organic carbon content quantified by titration and converted to MP mass[90]	(1) Robust and widely applicable for estimating total organic carbon (TOC); (2) particularly useful for assessing bulk organic content in mixed samples; and (3) does not rely on polymer type or physical characteristics, making it broadly applicable	(1) Fully destructive; samples cannot be recovered post-analysis; (2) limited ability to distinguish between different polymer types or provide morphological details; (3) may involve hazardous chemicals that require strict safety measures; and (4) may underestimate carbon content in samples with incomplete oxidation

Table 4 (*Contd.*)

MNP quantification methods	Technology	Instruments	Representative summary of analysis	Advantages	Disadvantages
	Photometric[83,84,86]	Smartphone[84,86] and turbidity meter[83]	In the studies by Gunther *et al.* and Koutnik *et al.*, MPs were quantified by filtering, Nile red staining, and smartphone imaging, with the images subsequently analyzed using an algorithm.[84–86] In the study by Lu *et al.*, PET fragment concentrations were determined from turbidity measurements, where light scattering was correlated with particle concentration[83]	(1) Both smartphone imaging and turbidity meters offer affordable and rapid approaches for quantifying microplastics without requiring complex or high-cost instrumentation; (2) easy to use and portable, making them suitable for field applications or use in low-resource laboratory settings; and (3) when combined with appropriate staining protocols or calibration curves, they allow for efficient, high-throughput analysis of multiple samples in a short period of time	(1) Limited sensitivity and specificity compared to advanced imaging or spectroscopy techniques; (2) may require precise staining and calibration for accurate results; and (3) external factors such as lighting conditions, dye behavior, and sample clarity can influence the results
Thermal/destructive	Gas chromatography/mass spectrometry[89]	Pyrolysis–gas chromatography-mass spectrometry[89]	50 μL subsamples were pipetted into sample cups using a glass-capillary micropipette and dried on a heating plate at 50 °C before being analyzed using a pyrolysis–gas chromatography-mass spectrophotometer[89]	(1) High sensitivity for detecting polymer-specific thermal degradation signatures; (2) suitable for complex mixtures, offering precise polymer identification; (3) can quantify individual polymer contributions in multi-polymer samples; (4) provides insights into thermal stability and degradation properties of polymers	(1) Instrumentation (*e.g.*, pyrolysis-GC/MS) is highly expensive and requires specialized training; (2) fully destructive, consuming the sample during analysis; and (3) relatively limited throughput due to longer analysis times, which may make it less favorable for high-volume studies

[a] The reliability of these quantification methods is closely tied to how samples are prepared. Procedures such as digestion to remove other organic materials, density separation, and filtration can significantly affect outcomes, and without standardized protocols, differences in preparation can lead to inconsistencies in reported MNP concentrations.

accelerated breakdown could release additional MPs that were previously trapped within these organic matrices, resulting in high correlations between them. In addition, MPs and TOC can originate from similar sources, such as road runoff, vegetation debris, and urban litter. This shared origin can lead to simultaneous increases in TOC and MP concentrations during storm events, resulting in their strong positive correlations. However, Kong *et al.* hypothesized that their high correlations are a result of MPs' high affinity for organic-polluted water.[6]

3.3 Quantification and characterization of MNPs in SWMEPMS

Currently, a variety of methods for quantifying and characterizing MNPs in water exist across the literature.[94,95] There is a need to develop standard methods to quantify and characterize MNPs in water, along with guidelines for appropriate application contexts. Early research on MNPs in water systems primarily relied on physical quantification methods, such as counting MNPs through direct visual inspection and measuring their mass.[94,96] These early techniques, however, were often inefficient and prone to errors due to their dependence on human observation. The accuracy of these methods was significantly affected by the observer's skill, the complexity of the sample composition, and the varying sizes of the MNPs. Given the continuous advancements in this field, this review examines and summarizes the analytical methods used in the eligible studies for quantifying MNPs in effluents from the SWMEPMS, as presented in Table 4.

In Table 4, we classed the MNP quantification methods into three categories, *i.e.*, physical, chemical, and thermal/destructive methods. Physical quantification methods involve various particle-counting techniques. Chemical approaches include exciting specific compounds or functional groups associated with MNPs at various wavelengths or using organic carbon to estimate the mass of MNPs. When using the particle excitation approach, some identification of polymer type may be achieved if a range of wavelengths is used. Thermal methods, which are capable of both quantifying and identifying the polymer type, are destructive; unlike physical and chemical methods, they prevent sample re-analysis or re-counting if needed.

MNPs in stormwater and stormwater management systems vary in their classification (Table 3). Therefore, accurate quantification is essential to assess their impact on the environment. Critically, the effectiveness of these quantification methods (Table 4) is strongly influenced by the sample matrix and preparation procedures, such as removal of organic matter *via* digestion, separating MNPs from heavier particles *via* density separation, and concentrating particles by size fractionation *via* filtration. In the absence of standardized protocols, these preparatory steps introduce additional variability and remain as a critical factor affecting the accuracy and comparability of MNP data across studies. All plastic quantification methods reported in Table 4 inherently depend on certain assumptions.[81] These assumptions can affect the accuracy and reliability of the quantification, leading to potential biases in the results. For example, physical quantification methods, such as visual identification using a microscope, might depend on the observer's skill, while chemical quantification methods, such as spectroscopy, may assume specific interaction patterns between light and MNPs. In Table 4, the two widely used quantification methods for MNPs in the reviewed studies are physical and chemical. Generally, each of the methods has its limitations. For example, while the physical method using microscopy facilitates direct visual identification of MNPs, it requires significant time and effort and may not effectively identify smaller particles, such as NPs. Gravimetric methods are simple and cost-effective but non-specific (*i.e.*, cannot differentiate between polymer types). Photometric methods leverage accessible technology but may depend on effective staining. Chemical methods, such as spectroscopy, provide high sensitivity and specificity but require expensive equipment and expertise, and their detection limits may vary depending on the polymer type, functional group abundance, and MNP size. For example, FTIR and Raman may not be suitable for detecting NPs, specifically, and FTIR may not effectively detect smaller MPs (<10–20 μm).[6,84,85,89] Wet chemistry offers quantitative estimates of MNPs, but the technique can be labor-intensive and particularly susceptible to human error. Thermal methods like pyrolysis–gas chromatography/mass spectrometry (pyrolysis-GC/MS) provide detailed chemical information but are destructive and costly. In any case, depending on the samples or MNP form to be analyzed, some of the quantification methods are more appropriate depending on the circumstance. For instance, Rasmussen *et al.* opted for pyrolysis-GC/MS to quantify TWPs in their samples, as the presence of carbon black in TWPs would interfere with focal plane array-based Fourier transform-infrared (FPA-FTIR) spectroscopy.[89] Although Raman spectroscopy is one of the most reliable techniques for MNP identification and quantification,[97] it was not specifically used as a quantification method in the eligible studies. However, both FTIR and Raman spectroscopy are excellent for characterization analysis, such as identifying functional groups, surface structures, and chemical bonds of MPs, thereby aiding in understanding their interactions with SWMEPMS.[54]

3.4 Experimental framework

This section reviews the diverse approaches taken to investigate the removal of MNPs using SWMEPMS. This review is crucial for evaluating the reliability and validity of the results. For instance, laboratory experiments provide control over variables and, therefore, a detailed physical understanding of the system. On the other hand, field studies maintain realistic environmental conditions, offering insights into additional influences or factors that impact the system. Table 5 summarizes the experimental frameworks and characteristics of the SWMEPMS discussed in this review, emphasizing the predominance of lab-based experiments. The data presented in Table 5 are critically reviewed in the subsequent sections. In these sections (*i.e.*, Sections 3.5 and 3.6), we synthesized and summarised the removal characteristics of MNPs by SWMEPMS explored in the

Table 5 Summary of the experimental framework and removal characteristics[a]

Experimental scale/MNP class	SWMEPMS class	SWMEPMS type	Engineered porous media	MNP particle size (μm)	MNP dosage (mg L^{-1})	Sample volume/mass	Removal mechanisms	Removal efficiency	Ref.
Field-based (MPs)	Pavement-based	Permeable pavement	Artificial granite and concrete (*i.e.*, a mixture of quartz powder, resin, and a sand layer)	20–<300	Up to 270 particle per L	Up to 1 L of effluent water	Accumulation	Up to 99.4%	6
Lab-based (MPs)	Pavement-based	Pervious pavement	Coarse aggregate, synthetic fibers, and fume silica composite	106–850	10 g L^{-1}	Up to 1 L of effluent water	Entrapment	—	88
Field-based (MPs)	Pavement-based	Permeable pavement	Concrete and asphalt, with and without cured carbon fibers	50	500 g/32 m^2	0.9 L of effluent water	Settlement and hydrophobic interaction	Up to 99.3%	81
Field-based (MPs) (only for TWPs)	Pavement-based	Permeable pavement	Crushed granite and gravel bound by polymer-modified bitumen	≥10–≤1000	Up to 479.70 mg m^{-2}	50 μL (each subsample volume)	—	An average of 105.02 mg m^{-2}	89
Lab-based (MPs)	Pavement-based	Permeable pavement	Fine gravel, coarse gravel, and drinking water treatment sludge	10–5000	Up to 11 030 MPs/experiment	Up to 0.7 L of effluent water	Accumulation	Up to 99.6%	54
Lab-based (MPs)	Trench-based	Novel modular filtration system	—	20–>1000	Up to 4890 g	—	Sedimentation	Up to 99%	91
Lab-based (MPs)	Trench-based	Infiltration system	Natural sand (quartz and feldspars)	25–581	0.5 g MP mixture (*i.e.*, 0.1 g each PA, PE, PPblixter, PP and PET fibers)	10 L of effluent water	Settlement, interception, agglomeration, and hydrophobic interactions	>99%	39
Field-based (MPs)	Trench-based (a non-vegetated sand filter)	Sand filter	Sand and gravel	10–100	Up to median 323 particles per L	Up to 1 L (subsample) of effluent water	Sedimentation	Up to 62.5% (based on the median removal efficiency)	87
Lab-based (MPs)	Trench-based	Infiltration system	Biochar (produced from jujube leaf waste) and sand	≤10	200	—	Entrapment, entanglement, electrostatic interactions, and surface complexation	>99%	90
Lab-based (MPs)	Trench-based	Sand filter	Quartz sand	20–520	0.01%	100 mL (for effluent sample) and 1 g (for oven-dried MP contaminated filter media)	Accumulation and trapping	—	84
Lab-based (MPs)	Trench-based	Sand filter	Sand and soil	<10–1500	0.1 g per filter media column	100 mL (for effluent sample) and 1 g (for oven-dried MP	Accumulation	> 90%	86

Table 5 (*Contd.*)

Experimental scale/MNP class	SWMEPMS class	SWMEPMS type	Engineered porous media	MNP particle size (μm)	MNP dosage (mg L^{-1})	Sample volume/mass	Removal mechanisms	Removal efficiency	Ref.
						contaminated filter media			
Lab-based (MPs)	Trench-based	Sand filter	Quartz sand	>50–1000	0.1 g per sand filter column	100 mL (for effluent sample) and 1 g (for oven-dried MP contaminated filter media	Straining, accumulation, and hydrophobic interactions	Up to 100%	85
Lab-based (NPs)	Trench-based	Infiltration system	Quartz sand, limestone, zeolites, and manganese sand grains	0.1	5	—	Electrostatic interactions, cation bridging, trapping, and stuck	Up to 93.33%	98
Lab-based (NPs)	Trench-based	Infiltration system	Sand and limestone-amended sand	0.1	5	—	Straining, electrostatic interaction, and cation screening and bridging	Up to 99.65%	82
Lab-based and computer-based (MPs)	Pavement-based	Permeable pavement	Permeable block (mixture of cement, aggregate, and fine stone), sand, and gravel	40 and 112	1	Up to 1.5 L of effluent water	Straining and adsorption	Up to 100%	92
Lab-based (MPs)	Trench-based	Sand filter	Quartz sand and attapulgite	1 and 1.1	5	—	Entanglement, aggregation, agglomeration, physisorption, and chemisorption	Up to 100%	83

[a] Removal efficiency reports the concentration of MNPs captured by the SWMEPMS under optimal conditions.

reviewed primary articles, discussing them in more detail with reference to the data in the Table.

3.5 Transport, removal mechanisms, and retention of MNPs in SWMEPMS

The transport and removal mechanisms of MNPs in SWMEPMS are influenced by various factors such as particle size, density, and surface properties of MNPs, as well as engineered porous media characteristics, water matrix, and environmental conditions. The studies reviewed provide insights into these mechanisms. Large PET fibers are predominantly retained within the initial filtration zone of the SWMEPMS inlet, as reported by Rullander *et al.*, following their findings in lab-scale horizontal flow sand filters, where most MP fibers were retained close to the inlets of the lab models.[39] Other studies have linked increasing MP density to higher mobility in vertical columns, often resulting in deeper penetration within the filter media, where removal occurs at varying depths.[85,86] MNP surface properties also play a significant role in mobility and retention. For example, UV exposure alters MNP contact angle and surface hydrophilicity, enhancing downward mobility,[84] consistent with the extended Derjaguin–Landau–Verwey–Overbeek (XDLVO) theory.[99] The authors also observed an increase in downward mobility of MPs due to freeze-thaw cycle processes attributed to the influence of the MNP-water-media interface on heat transport and ice crystal growth processes.[84] This aligns with other studies that have observed increased MNP mobility in SWMEPMS due to freeze-thaw cycles. For example, Koutnik *et al.* examined the transport and redistribution of MPs in SWMEPMS using PP, PS, and PET.[85] They observed that the downward mobility of denser MPs was increased after 36 freeze-thaw cycles.[85] Using a force balance model, the authors also demonstrated that MPs less than 50 μm can be propelled at a higher velocity by the ice–water interface, regardless of their density. However, for MPs greater than 50 μm, the plastic particle density becomes a significant factor.[85] A similar study conducted by Koutnik *et al.*, supported these findings.[86] They found that the freeze-thaw treatments enhanced the downward transport of MPs, resulting in a concentration profile that decreases exponentially with depth.[86] Therefore, we hypothesize that with sufficient historical data, analytical probabilistic models can be developed to predict the distribution of MNPs in SWMEPMS.[53] This study also noted that the presence of soil in sand filters limits MP mobility by blocking pore paths, thereby amplifying the effects of freeze-thaw cycles in sand-only columns.[86] Collectively, these findings underscore the importance of MNP and engineered porous media properties, as well as environmental conditions, on the efficacy of SWMEPMS for MNP removal.

The transport mechanism of MNPs in SWMEPMS can be significantly influenced by the MNP form, as shown in Tables 3 and 5. For example, Rullander *et al.* used horizontal flow sand filter columns to treat stormwater, and observed that more than 98% of MPs, including high-density fibers and fragment-form MPs, were effectively retained within the filter media.[39] A significant portion of these agglomerated within the first few centimetres of the filter media, which was attributed to the tendency of these particles to become entangled within the engineered porous media.[39] However, permeable pavement stormwater management structures have more difficulty retaining fragment-form MPs due to the configurations of these structures, especially for porous concrete pavement configuration.[54] Furthermore, permeable pavement may not remove smaller MNPs permanently;[54] they may be released at a later time when conditions change. These findings highlight potential limitations of permeable pavement structures for long-term MNP retention, although broader research across a wider range of conditions is needed before firm conclusions can be drawn.

Recent studies on the transport mechanisms of NPs provide additional insights into the limitations of SWMEPMS. Wang *et al.* explored the transport of NPs in various porous media, including quartz sand, zeolite, and limestone.[98] The findings indicated that the size and specific surface properties of NPs and the filter media resulted in higher mobility and reduced interaction, leading to increased transport through the media. Another study by Li *et al.* found that the transport of NPs in sand-limestone columns was significantly influenced by the surface characteristics of the porous media and the background solution chemistry.[82] The study demonstrated that NPs exhibited different transport behaviors depending on the porosity and surface roughness of the filter media, with higher flow velocities increasing NP mobility. It was observed that the distribution of NPs within the filter media was uneven, with higher concentrations of NPs found in areas where the flow was slower or where there were physical barriers to movement. Therefore, collectively, these studies indicate that the transport of MNPs may be affected by the physical structure of the filter media, including pore size and pore throat structure, which can alter flow paths and particle movement.

The removal mechanisms outlined in Table 5 highlight the various processes through which MNPs are removed by different SWMEPMS. Retention of MNPs in SWMEPMS is primarily influenced by DLVO and XDLVO forces, where (i) the MNP must approach or contact the filtration media, and (ii) attractive forces, such as van der Waals (DLVO) and acid–base interactions (XDLVO), must exceed or counterbalance the dominant repulsive electrostatic forces governed by the electric double layer. As stormwater passes through engineered porous media, MNPs may interact with the media through a variety of mechanisms, including interception, diffusion, inertia, sedimentation, hydrodynamic forces, straining, and charge exclusion.[100–102] However, research in SWMEPMS to date has only identified mechanisms leading to retention, as shown in Table 5. In some cases, retention results from sedimentation, where particles settle out due to gravity, as observed in SWMEPMS employing engineered sand and gravel media.[81,87,91] Lange *et al.* observed that sedimentation may be insufficient to remove lower-sized MPs (*i.e.*, 20 to 100 μm) from highway stormwater due to their small size and/or low density, which prevents effective settling and allows them to remain suspended in water in the engineered porous media.[87] Another critical mechanism that can lead to retention is straining,[82] which occurs when the MNP size exceeds that of the pore throat.

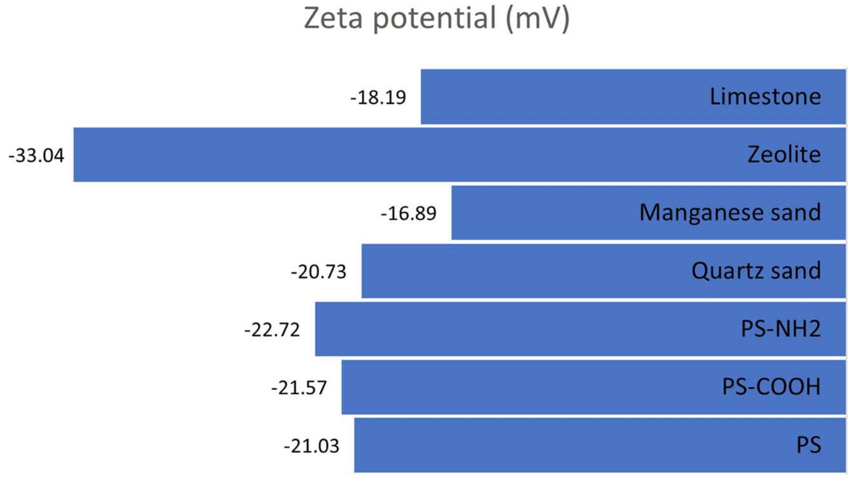

Fig. 5 Zeta potential of NPs and some of the engineered porous media (designed by the authors of this present work using the data reported by Wang *et al.*).[98] Deionized water was the background solution used for measuring the zeta potential of the NPs and engineered porous media. The NPs used were pristine polystyrene (PS), amino-modified polystyrene ($PS-NH_2$), and carboxyl-modified polystyrene (PS–COOH).

Entanglement and entrapment mechanisms are specifically noted in biochar-based SWMEPMS, where the fibrous structure of the media physically entangles and traps particles.[90] Surface roughness of the media also contributes to MNP-media interactions, providing more area for NPs to adhere to and become trapped. This is particularly effective in materials in trench-based SWMEPMS encompassing quartz sand, limestone, zeolites, manganese sand grains, and limestone-amended sand.[82,98]

Electrostatic and hydrophobic interactions are critical mechanisms for the removal of MNPs by SWMEPMS, particularly under specific water chemistry conditions. These interactions can either retain or repel MNPs when they approach or contact the media surface. Electrostatic forces are notably effective in biochar produced from jujube leaf waste, sand, and limestone-amended sand.[82,90,98] Hydrophobic interactions have also been found effective in SWMEPMS utilizing materials like natural sand, concrete and asphalt with carbon fibers.[39,81,85] Experimental evidence from Ahmad *et al.* demonstrated that electrostatic interactions predominantly facilitated the removal of MPs when biochar was employed as the engineered porous media within a trench-based SWMEPMS.[90] Water chemistry conditions, particularly pH variations, can significantly influence zeta potential, thereby affecting the retention of MNPs through electrostatic and hydrophobic interactions. For example, for NPs, Li *et al.* observed that the zeta potentials of quartz sand, limestone, and NPs all became less negative in artificial wastewater compared to deionized water, shifting from −21.87 to −19.53 mV (quartz sand, 20–30 mesh) and −25.87 to −17.47 mV (quartz sand, 40–50 mesh), −18.90 to −10.57 mV (limestone), and −32.50 to −29.83 mV (NPs), respectively; this reduced electrostatic repulsion and consequently enhanced NP immobilization within the filtration columns.[82] However, supporting evidence also indicates that, under low ionic strength, electrostatic interactions alone may be insufficient for effective retention of MNPs in some media, for example, in quartz sand. In one study, transport of PS MPs was still observed at 10 mM NaCl and 1 mM $CaCl_2$, with ∼5% of MPs passing through quartz sand filters. Only at higher ionic strengths (100 mM NaCl and 10 mM $CaCl_2$) was complete removal achieved, consistent with the predictions of DLVO theory.[83] Moreover, the addition of attapulgite significantly reduced PS MP transport regardless of ionic composition, suggesting that the presence of co-solutes or solution chemistry exerts a complex influence on retention performance.[83]

Several studies have examined the effects of polymer type on removal mechanisms, finding that polymers with higher charges are more effectively removed through electrostatic interactions.[90,98] In addition, the surface properties of MNPs may be altered by UV exposure, which can lead to the formation of polar functional groups, such as hydroxyl, carbonyl, and amino groups, on their surfaces. These changes increase the hydrophilicity of the particles and can significantly influence their removal behavior *via* the influence of removal mechanisms, such as electrostatic interactions, depending on the engineered porous media and the background solution.[98]

Furthermore, as shown in Fig. 5, the study by Wang *et al.* noted that the zeta potential of manganese sand was less negative than that of quartz sand, limestone and zeolite grain[98] Despite this, the difference in zeta potential was insufficient to effectively retain NPs under high flow conditions; this is because the smooth surface of the manganese sand, when compared to quartz sand and zeolite grains, making it more difficult for it to retain the NPs.[98] As indicated in Table 5, other important removal mechanisms include cation bridging and screening. These mechanisms enhance particle retention by mediating interactions through cations, either by forming ionic bridges between negatively charged surfaces (cation bridging) or by compressing the electric double layer to reduce electrostatic repulsion (cation screening). Such effects have been observed in media like quartz sand and limestone-amended sand and promoted by competing ions.[82,98] For instance, in the study by Li *et al.*, monovalent ions, such as sodium (Na^+) and potassium (K^+), in contaminated water favored the immobilization of NPs due to the cation screening effect, while divalent cations, such as calcium (Ca^{2+}) and magnesium (Mg^{2+}), further enhanced NP retention by contributing to both stronger double-layer compression and cation bridging.[82] In the case of limestones as engineered porous media, the calcium ions, along with competing ions, carboxylic and hydroxyl groups, detected on the limestones' surfaces, further and strongly enhanced the bridge effect, thereby enhancing the removal of NPs from contaminated water.[82] Similarly, Wang *et al.* stated that calcium ions released by limestone into contaminated water can facilitate the removal of NPs either through cation bridging or by decreasing the electrostatic repulsion between the NPs and the engineered porous media.[98] In a related recent finding, attapulgite, a metal oxide-rich clay, demonstrated enhanced adsorption of MPs due to active binding at Ca^{2+} and Al^{3+} sites.[83] These metal cations served as key adsorption sites,[103] inducing charge density redistribution at the interface between attapulgite and the C–H bonds of MPs, thus contributing to stronger retention interactions.[83]

The surface roughness of engineered porous media can also play a significant role in retaining MNPs. Studies by Wang *et al.* indicated that the physical "trapped" effects, especially due to limestone roughness, effectively mitigate the influence of functional groups on NP surfaces, leading to efficient retention.[98] These results indicate that both the chemical and structural characteristics of the media may be critical for the retention of MNPs. Another critical factor that determines the retention of MNPs in SWMEPMS is the ratio of engineered porous media diameter (dm) to the suspended particle diameter (dp) (*i.e.*, dm : dp). This ratio demonstrates that SWMEPMS properties are an important design consideration for MNP removal. The media size and roughness impact physical removal mechanisms, while surface properties facilitate the retention of smaller MNPs through physico-chemical mechanisms. For instance, Rullander *et al.* suggested that the retention of MPs can be observed if the mean particle diameter is greater than 5–10% of the porous media's mean particle size.[39] The authors further stated that the removal of larger MPs with media-to-particle diameter ratios less than 10 (*i.e.*, dm : dp < 10) is expected to be predominantly straining (mechanical removal and clogging of filter surfaces). In comparison, the removal of smaller MPs with ratios larger than 1000 is predominantly dominated by physico-chemical mechanisms.[39] Additionally, the study observed smaller MPs of 25–30 μm in SWMEPMS effluents and attributed the lack of retention to the relatively large dm:dp ratio (∼68) and relatively low density.[39] Although this supports the general understanding that larger MNPs, by reducing the dm:dp ratio, are more likely to be retained *via* straining, Kong *et al.* observed an important polymer-specific nuance; in their pavement-based experiment, larger PET particles penetrated pore structures more readily and were less likely to be retained, whereas smaller PE particles easily entered and became trapped within pore channels, enhancing their adsorption.[92] Here, we recognise that surface complexation, a process involving the formation of coordination complexes, may play a key role in retaining smaller MNPs, which possess a higher surface area-to-volume ratio and, therefore, a greater potential to interact with reactive sites on the engineered porous media. This reinforces the notion that MNP polymer type, particle size, as well as the engineered media size, roughness, surface properties, and pore geometry act in concert to govern MNP removal efficiency in porous media systems. This is further supported by microscopic evidence presented in Fig. 6 and 7, which illustrate various MNP removal mechanisms, such as straining, adsorption, and entanglement across different engineered porous media, including concrete, sand, limestone, and jujube-derived biochar.

Although this remains an argument,[39] we posit that the primary difference in the removal mechanisms of MPs and NPs by SWMEPMS stems from the significant size difference. Specifically, the removal of MPs is largely governed by hydrodynamic forces, including physical processes such as filtration, settling, and interception, which are typically influenced by gravity (Table 5). In contrast, the removal of NPs predominantly occurs through adsorption driven by physico-chemical interactions.[67] For illustration purposes, in Fig. 8, using one of the most widely used trench-based SWMEPMS, highway filter drains (HFDs),[53] we showed our suggested HFD modification and its removal mechanism of MNPs, taking into consideration the typical design criteria of HFD, MNP surface properties, and functional groups.

3.6 Removal efficiency of MNPs by SWMEPMS

As shown in Table 5, the removal efficiency of MNPs in various SWMEPMS varies significantly depending on the type of engineered porous media and experimental conditions. In a field-based study, permeable pavements incorporating artificial granite and concrete achieved removal efficiencies of up to 99.4%, primarily through filtration.[6] These systems handled up to 270 particles per L of MPs, demonstrating a high capacity for particle retention even at relatively high dosages. Conversely, a lab-based experiment using trench-based SWMEPMS with sand and gravel achieved a lower removal efficiency of 47.39% despite a smaller MP concentration of 230 particles per L.[87] The reduced efficiency in that study can be attributed to differences in pore structure and hydraulic behavior.

In another study, Mitchell and Jayakaran observed that field-based permeable pavements made of concrete and asphalt, with and without cured carbon fibers, exhibited removal efficiencies exceeding 96%.[81] These systems effectively managed an MP dosage of 0.9 g per 32 m^2 area through mechanisms including sedimentation and hydrophobic interactions. However, a similar experimental setup showed an average retention of 105.02 mg m^{-2} from an MP dosage of 479.70 mg m^{-2}, indicating challenges in capturing this type of MP within the pavement systems.[89] Generally, the design of permeable pavements often prioritizes porosity for effective water infiltration, which can compromise the ability to capture TWPs. However, the addition of materials like cured carbon fiber composites can enhance MP removal as well as the mechanical properties, though it is costly and not universally applicable.[81]

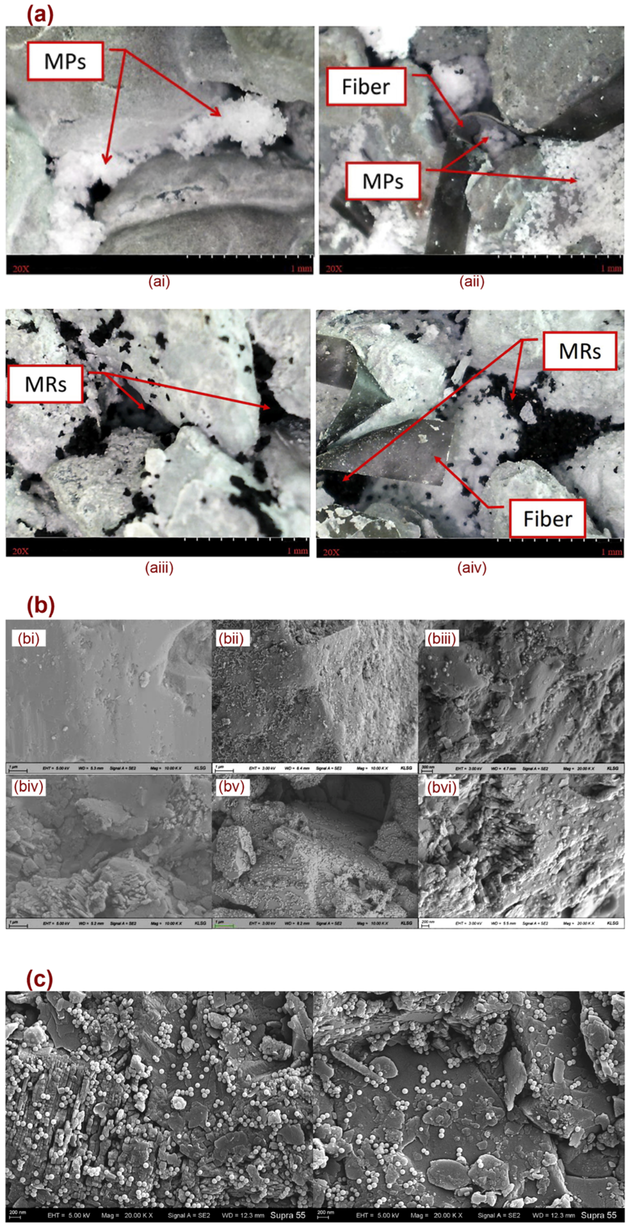

Fig. 6 Microscopic images showing some of the removal mechanisms of MNPs by SWMEPMS (adapted from Li *et al.*, Tran *et al.*, and Wang *et al.*, all with permission from Elsevier,[82,88,98] copyrights 2022, 2020, 2024, respectively). This composite figure presents microscopic images from three different studies to illustrate the removal mechanisms of MNPs by various porous media. Subfigure (a) shows digital microscopic images depicting MPs and microrubbers (MRs) retained within the matrices of plain concrete (PC) and fibre-reinforced pervious concrete (FRPC) after the filtering process: in (ai) PC–MPs, a larger amount of MPs are trapped within the plain PC matrix with small aggregates than those with large aggregates, demonstrating the greater ability of plain concrete to effectively filter and retain MPs; in (aii) FRPC–MPs, MPs are trapped within the FRPC matrix (the presence of fibres, made from recycled high-density polyethylene (HDPE), enhances the filtration capacity by filling voids and trapping more MPs compared to plain concrete); in (aiii) PC–MRs, MRs are trapped within the plain concrete matrix, indicating the capability of plain concrete to filter and retain these rubber particles; in (aiv) FRPC–MRs are trapped within the FRPC matrix, where the fibres help trap more MRs by filling voids and enhancing the filtration capacity compared to plain concrete. Subfigure (b) presents scanning electron microscopic (SEM) images of different engineered porous media, emphasizing the role of surface smoothness and roughness in NP removal; in (bi) and (div), the images show the surfaces of quartz sand and limestone as the engineered porous media, respectively, before any NP removal, displaying their original surface textures; in (bii) and (bv), the SEM images illustrate quartz sand and limestone grains after NP removal at a flow rate of 3 mL min^{-1}, showing the removal of NPs on both the smooth and rough surfaces; in (biii) and (bvi), the images show the quartz sand and limestone grains after NP removal at a higher flow rate of 21 mL min^{-1}, revealing a lower removal of NPs on both smooth and rough surfaces. Finally, subfigure (c) showcases SEM images of how NPs were mostly found on the rough surfaces of limestone, where they tended to get trapped in widely distributed grooves and ravines. This is because grooves and ravines provide areas where NPs can be physically trapped due to the depressions in the surface of the media. NPs can also be noticed to be stuck in matching spots due to the engineered porous media and the contaminants having specific points where the surfaces' shapes are similar. Together, these images illustrate the physical mechanisms of MNP retention and, when considered alongside supporting studies, also reflect the role of chemical interactions that govern the removal efficiency of SWMEPMS for MNPs.

Furthermore, Lab-based permeable pavements using a combination of fine gravel, coarse gravel, with or without drinking water treatment sludge drinking water treatment sludge demonstrated removal efficiencies ranging from 77.8% to 96.7% (up to 99.6% for TWPs), handling MP dosages between 2503-11030 MPs/experiment.[54] The varying efficiencies underscore the impact of both the material composition and the MP concentration on system performance. For instance, a novel modular filtration system simulated by Venghaus *et al.* achieved a 99% removal efficiency for PE pellets with a dosage of 4890 g but only 21% for tire powders with a dosage of 1000 g,[91] highlighting the significant influence of particle type and dosage on removal outcomes. Overall, these findings suggest that urban stormwater management strategies may need to be tailored to the specific characteristics and morphology of MNPs in urban runoff to improve removal effectiveness and better protect receiving water bodies.

Ahmad *et al.* demonstrated that biochar produced from jujube leaf waste, used in a trench-based SWMEPMS lab experiment, achieved over 99% efficiency compared to up to 78% for sand at a dosage of 200 g L^{-1}.[90] This highlights the significant role of biochar as a nature-based engineered porous media in enhancing removal efficiency through filtration, entrapment, electrostatic interactions, and surface complexation. In addition, studies by Gunther *et al.*, Koutnik *et al.*, and Koutnik *et al.* confirmed the efficacy of sand filters, a trench-based SWMEPMS, in removing MPs *via* accumulation, physical straining, and hydrophobic interactions, even at low dosages of between 0.01% to 0.1.[84–86] Notably, Koutnik *et al.* reported removal rates exceeding 90%.[86]

For NPs, removal efficiencies varied significantly among different filter media: quartz sand, manganese sand-quartz sand, zeolite-quartz sand, and limestone-quartz sand achieved removal efficiencies of 8.81%, 11.01%, 61.16%, and 93.33%, respectively.[98] Quartz sand exhibited minimal NP removal, attributed to the strong electrostatic repulsion between the sand grains and NP particles, coupled with the smooth surface

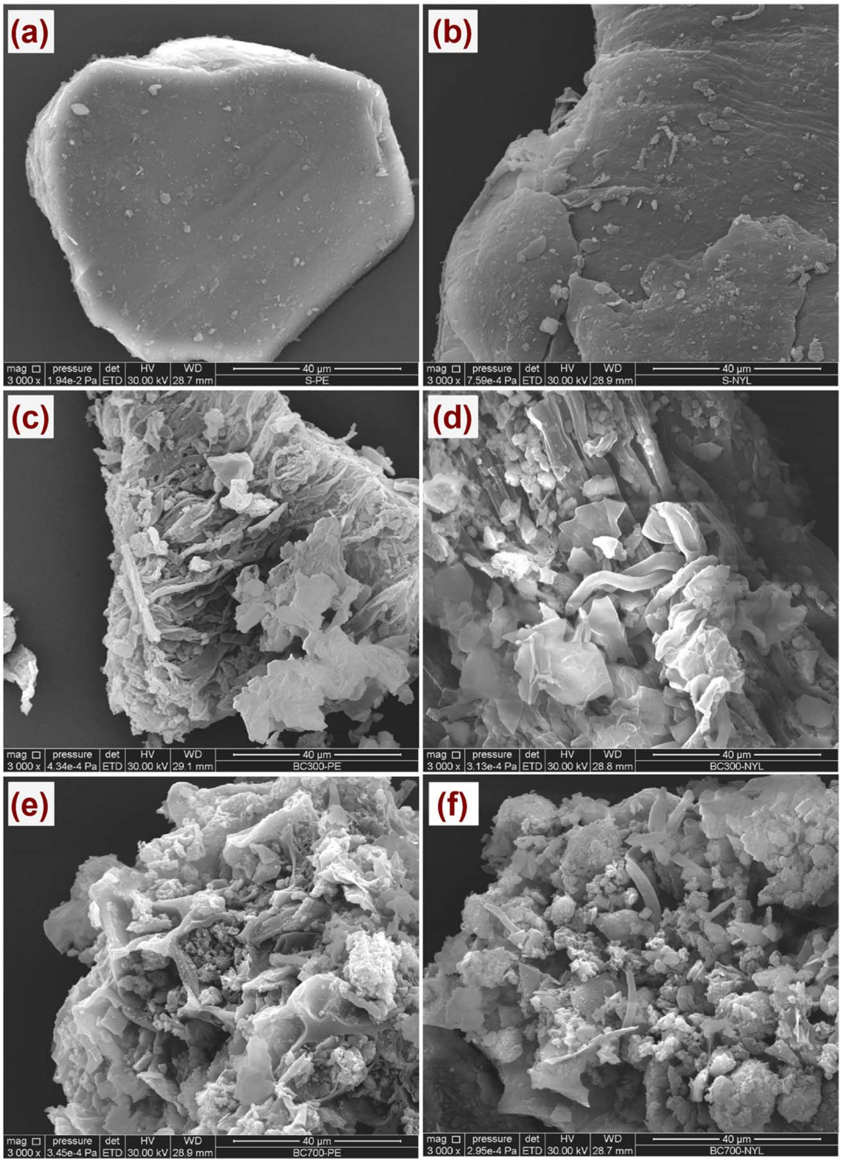

Fig. 7 SEM images showing several removal mechanisms, including adsorption, stuck, and entanglement, of MPs by jujube waste-derived biochar in a simulated trench-based SWMEPMS (adapted from Ahmad *et al.*, with permission from Elsevier,[90] copyright 2023). This figure highlights various removal mechanisms by which MPs are retained on sand and biochars derived from jujube waste at two different pyrolysis temperatures: (a) shows PE particles adsorbed onto the surface of sand. We suggest that the smooth surface of the sand may have provided limited attachment points for the PE particles, with retention occurring mainly through weak surface attachment and the 'stuck' mechanism, where particles became immobilized within the large inter-particle voids; (b) illustrates how nylon particles were retained on sand, similar to PE, with removal limited to weak attachment on the relatively smooth surface and dominated by the stuck mechanism within pore spaces between sand grains; (c) depicts how PE particles were adsorbed on biochar produced at 300 °C. The biochar's surface, characterized by a more porous and rough structure compared to sand, appeared to enhance the entanglement and physical trapping of PE particles; (d) shows how nylon particles interacted with the biochar surface produced at 300 °C. The rough and porous nature of the biochar may have aided in the adsorption and retention of nylon particles, likely through a combination of physical entanglement and electrostatic interactions; (e) illustrates how PE particles were adsorbed on biochar produced at 700 °C. The higher pyrolysis temperature may have resulted in a biochar with an even more developed porous structure, providing more surface area for the adsorption and retention of PE particles; (f) displays how nylon particles were adsorbed on the highly porous surface of biochar produced at 700 °C. The biochar's enhanced structure may have led to the effective removal of nylon particles, primarily through entanglement within the biochar's porous matrix and potentially stronger electrostatic interactions due to the presence of functional groups on the biochar surface.

of the sand, which hindered retention. The incorporation of manganese into sand did not significantly enhance NP removal, as the manganese sand's surface smoothness and marginally less negative zeta potential were insufficient to retain NPs under high flow conditions. Zeolite-quartz sand filters also proved ineffective, largely due to the small size of the NPs, which allowed them to pass through the filter unimpeded. In contrast, limestone-quartz sand demonstrated the highest removal

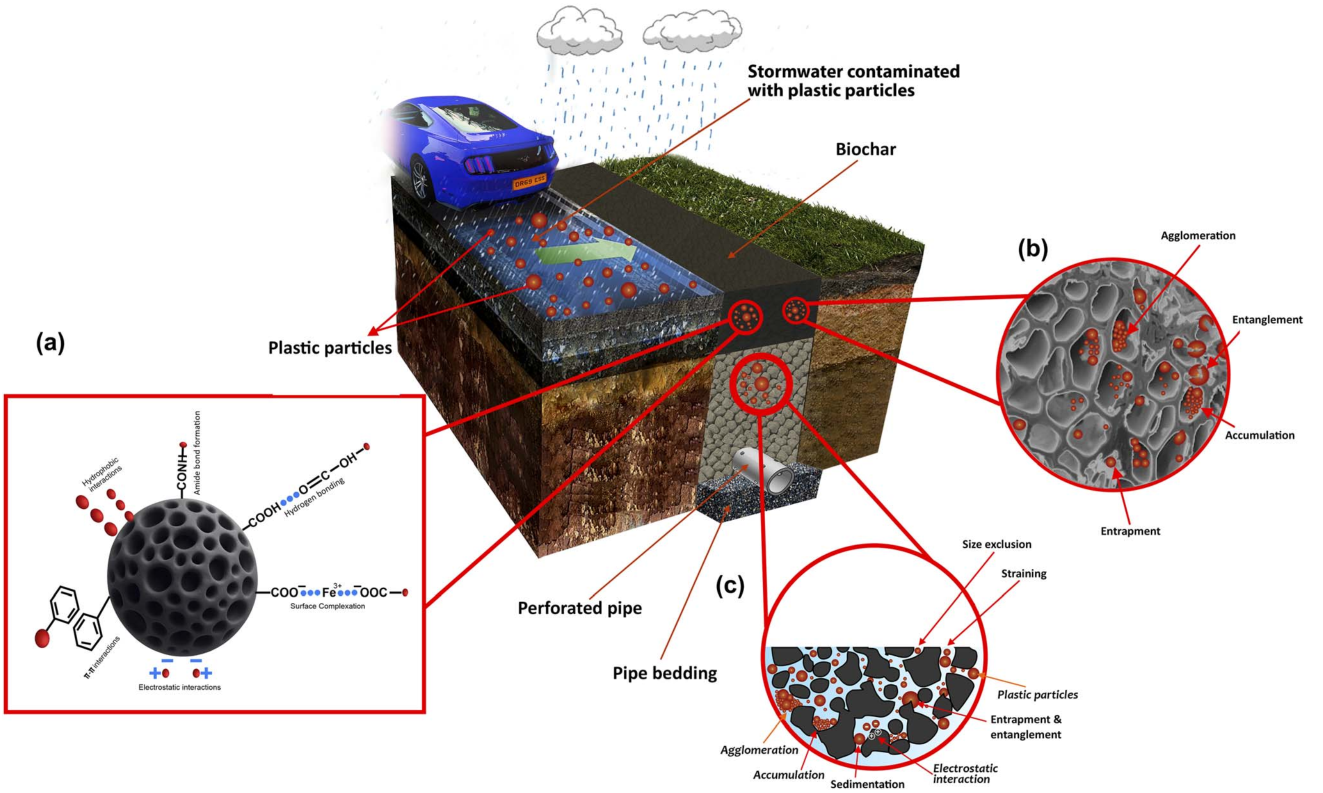

Fig. 8 Our suggested removal mechanisms of MNPs using modified HFD, a trench-based SWMEPMS (designed by the authors of this present study). (a) The removal mechanism is dominated by adsorption, especially for NPs, on the surface of the biochar, and (b) and (c) the removal mechanism is dominated by filtration within biochar and stone aggregate, respectively.

efficiency. The superior performance of limestone was ascribed to its rough surface morphology, which provided physical traps for NPs, and the high calcium content that facilitated cationic bridging, enhancing NP retention. Furthermore, Li *et al.* also observed that sand and limestone-amended sand filters could achieve removal efficiencies up to 99.65% for NPs, with the removal being influenced by physical straining, electrostatic interaction, and surface roughness.[82] Both studies highlighted the critical role of both the physical structure and chemical composition of engineered porous media, especially limestone, in the effective removal of NPs from aqueous solutions.

Beyond the type of engineered porous media, an important factor influencing removal efficiency is the particle size of the MNPs investigated. Across the reviewed studies, the size ranges varied considerably, with a maximum particle size of 100 nm for NP studies and ranging from ≤10 μm to 5000 μm for MP studies. The variability complicates direct comparison of results, as smaller particles generally exhibit higher mobility and are more difficult to retain in porous media, whereas larger particles are more readily retained through physico-chemical processes. For example, in a trench-based LID, Rullander *et al.* reported that MPs smaller than 50 μm were most frequently detected in the effluents, while larger MPs (>100 μm) were more effectively retained in the engineered porous media.[39] Several other LID-based studies support these findings.[6,84,86–88] Extending this work to other stormwater control measures, García-Haba *et al.* observed that permeable pavements struggled to retain the smallest fraction of MPs (<100 μm), which was the most frequently detected particle size range in the effluents compared to relatively larger fractions (100–5000 μm).[54] Notably, in the same study, TWPs exhibited the highest removal efficiencies (up to 99.6%), and the smallest influent TWP size identified was 80 μm,[54] underscoring that retention is impacted by factors beyond particle size. This highlights the importance of harmonizing size class definitions in MNP research, for example, by adopting common, environmentally relevant bins, thereby enabling more consistent cross-study comparisons and supporting systematic investigation into how MNP size influences retention mechanisms and removal efficiencies within different SWMEPM configurations.

From our review, we hypothesize that there are two major critical factors affecting removal efficiency in both the pavement-based and trench-based SWMEPMS. The first is the morphology and surface properties of engineered porous media as well as those of the MNPs, and the second is the environmental condition, including the stormwater chemistry. For example, in the case of the aggregate size of the engineered porous media, changes in the aggregate size of the engineered porous media can significantly impact the MNP removal efficiencies.[81,88,98] In the case of MNPs, smaller MNPs are often more mobile, thereby escaping capture and retention in SWMEPMS.[6,54,98] Additionally, the role of geotextiles within

SWMEPMS structures is crucial, particularly for retaining fibers, which are often challenging to capture and retain by SWMEPMS.[54] Upper geotextiles in SWMEPMS, like permeable interlocking concrete pavements, captured a higher percentage of fibers compared to lower layers, demonstrating the importance of material placement and selection.[54] This is an important aspect to consider when designing highway filter drains, which is one of the most widely used trench-based SWMEPMS.[53] Flow velocity is another key factor influencing MNP removal efficiency by SWMEPMS. Lower flow rates allow for prolonged contact time, enhancing the potential for interactions between NPs and the engineered porous media, thereby improving removal efficiency.[82] For MPs, longer engineered porous media length and lower flow rates are associated with higher retention, emphasizing the importance of design considerations in optimizing SWMEPMS systems.[39] Fiber retention efficiency also varies significantly with polymer type; for instance, PET fibers were completely retained by most engineered porous media, whereas PP fibers, despite high removal efficiency, still appear in some effluents.[39]

3.7 Strategies for optimizing SWMEPMS' MNP removal efficiency

Based on our systematic and comprehensive review, we suggest that various strategies targeting the maintenance, design, and operational aspects of SWMEPMS may be implemented to optimize their MNP removal efficiencies. For example, clogging remains the most prevalent maintenance concern for both pavement and trench-based SWMEPMS.[53,104] Therefore, regular inspection and maintenance are essential to prevent clogging and ensure the optimal functioning of SWMEPMS. Accumulated debris and sediment can reduce the porosity and permeability of the engineered porous media, thereby decreasing their efficiencies. For instance, beyond dm : dp ratios (Section 3.5.), the relationship between permeability and porosity could impact MNP retention. However, studies examining the statistical correlation between these variables remain limited. One such study conducted a correlation analysis for PE and PET in synthetic rainwater and found a strong upward linear relationship between permeability and porosity (correlation coefficients of 0.8767 and 0.9902, respectively).[92] Increased porosity was shown to enhance the effective surface area within permeate blocks, improving particle capture by providing more adsorption sites.[92] This suggests that maintaining permeability could be critical not only for sustaining infiltration rates but also for maintaining MNP removal performance. Monitoring should include assessing the physical condition of the media, checking for blockages, and measuring infiltration rates. Scheduled maintenance activities, such as removing surface debris and periodically replacing or replenishing the porous media, may help sustain high removal efficiencies.

The composition of engineered porous media significantly influences the removal efficiency of SWMEPMS. Therefore, selecting materials with appropriate grain sizes, surface properties, and chemical characteristics may enhance the system's ability to capture and retain plastic MNPs. For example, incorporating nature-based adsorbents, such as biochar and activated carbon, which have proven to be effective in removing MNPs,[90,105,106] can increase SWMEPMS's removal efficiency, especially for smaller plastic particles, such as NPs. Moreover, utilizing a combination of porous materials with different properties can provide a more comprehensive filtration system capable of capturing a broader range of particle sizes and polymer types.

Integrating geotextiles within SWMEPMS, especially for trench-based SWMEPMS, may help enhance the capture and retention of MNPs. Geotextiles can act as a secondary barrier, preventing the migration of small particles into lower layers of the system or groundwater. Additionally, when used as a barrier between native soil and engineered porous media, geotextiles can mitigate the introduction of native soil into engineering porous media as a result of side infiltration, which can be particularly beneficial in stormwater sand filters and HFDs. For pavement-based SWMEPMS, a recent study verified that permeable pavement structures that utilized two geotextiles showed higher MP and TWP removal efficiencies than those with one geotextile layer.[54] These findings indicate that the number and configuration of geotextiles can influence performance. In addition, in designs intended for water storage and reuse, wrapping drainpipes with geotextiles may help retain particles while maintaining permeability.[54] Generally, the inclusion of filtration layers with varying permeability can create a gradient filtration effect, thereby enhancing overall system efficiency.

Given the increasing impact of climate change, SWMEPMS should be designed to accommodate seasonal changes and environmental conditions, such as freeze-thaw cycles, heavy rainfall, and temperature fluctuations. This is particularly important in regions known for extreme weather conditions, including Canada, Northern China, Japan, the northern and midwestern states of the USA, and parts of Europe. For instance, during winter, freeze-thaw cycles can remobilize previously captured particles, while heavy rainfall events can introduce large loads of MPs.[85,86,89] Consequently, implementing design features that account for these variations, such as adjusting the media composition or adding protective layers, can help maintain the system's efficiency throughout the year.

Utilizing sustainable, recyclable, and locally sourced materials in the construction, maintenance, and retrofitting of SWMEPMS can promote environmental sustainability and reduce costs. Materials such as recycled aggregates, biochar derived from organic waste, and non-plastic-based geotextiles like natural fibers offer environmentally friendly alternatives to conventional materials. These materials not only contribute to the system's efficiency but also align with broader UN sustainability goals, as outlined in the Introduction section. Moreover, the use of plastic-based geotextiles can introduce plastic particles to the system over time due to material degradation.[54]

Finally, raising public awareness about the importance of SWMEPMS and proper waste disposal practices can significantly impact the system's effectiveness. Educating the public and relevant stakeholders, including industries, about the importance of proper waste disposal practices and the consequences of plastic pollution can promote responsible behaviors and reduce the burden on stormwater management systems. In general, engaging stakeholders, including local authorities, businesses, and residents, in maintaining and supporting SWMEPMS systems can lead to better management and higher operational standards.

3.8 Knowledge gaps and directions for future study

The research area of MNP removal using SWMEPMS is burgeoning, yet several critical knowledge gaps remain that hinder a comprehensive understanding of the underlying processes. Identifying these gaps is essential for guiding future research and enhancing the efficiency, scalability, and sustainability of SWMEPMS applications.

As highlighted in previous sections, MNPs are present across multiple environmental compartments, particularly aqueous systems, and their pollution impacts all three pillars of sustainability (environmental, social, and economic). Despite this widespread presence, there is a lack of comprehensive data on their availability, distribution, and impact on the three pillars of sustainability, limiting the development of a detailed coupled system. To frame these broader implications and support the identification of future research directions, we present a coupled-systems conceptual model (Fig. 9). This model illustrates the sources, pathways, and feedback loops linking plastic particle pollution to the three sustainability pillars. The model highlights how plastic particle pollution, originating from anthropogenic and industrial activities, spreads through environmental compartments and ultimately impacts human wellbeing and economic systems. For environmental sustainability, it incorporates factors such as air, water, and food quality. For social sustainability, it includes holistic wellbeing—physical, mental, emotional, and spiritual health. Economic sustainability is represented by healthcare costs, tourism impacts, and remediation costs. The model also visualizes feedback loops; for instance, degradation in environmental quality may increase healthcare costs or reduce tourism, while public health crises can drive policy changes or investments in solutions like SWMEPMS. A recent example is the UK's 2023 commitment to improve access to green spaces and water within a 15-minute walk for all residents, thereby promoting infrastructure like SWMEPMS.[107] The systems-level

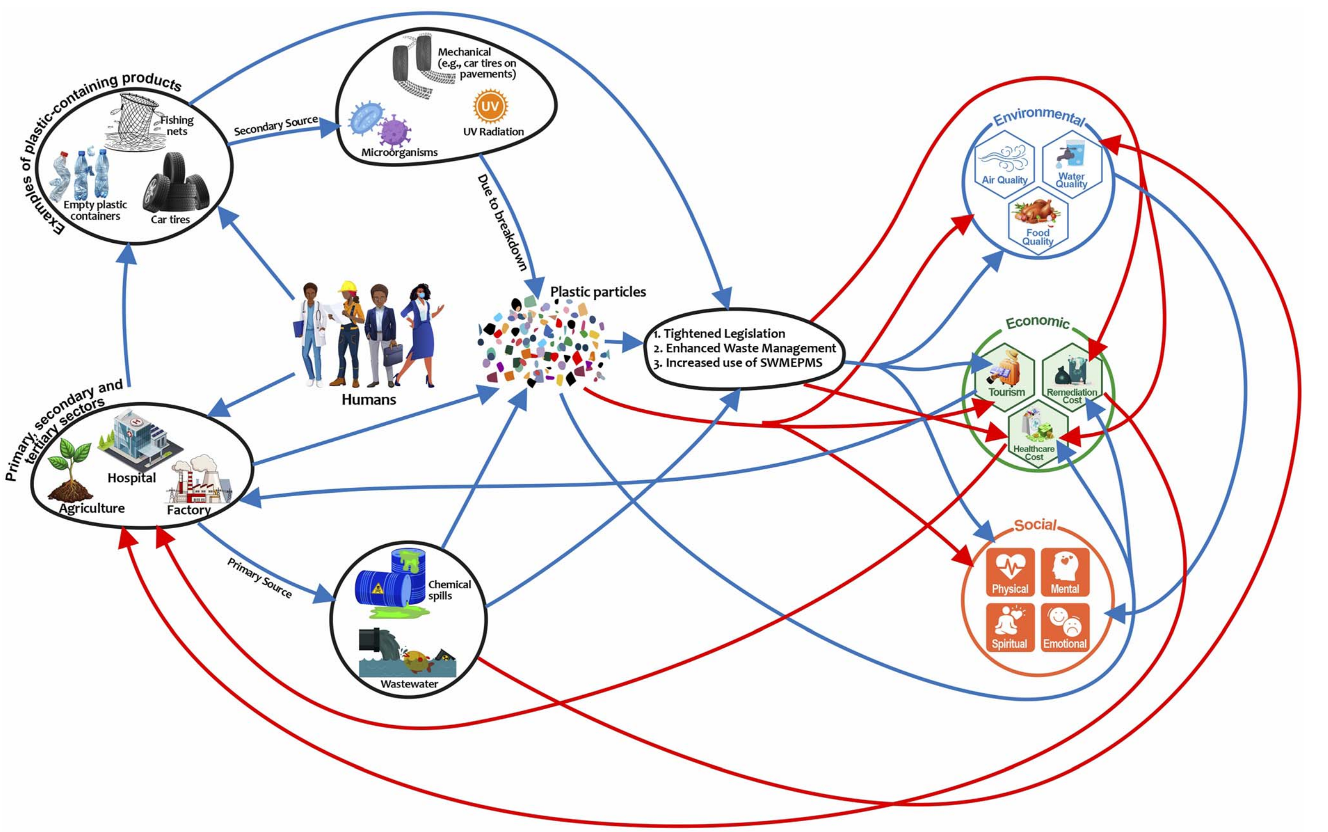

Fig. 9 Causal loop diagram of MNP-coupled system (designed by the authors of this present study). The three pillars of sustainability comprise environmental, social, and economic sustainability.[4] For simplicity, selected themes relevant to each pillar were incorporated. For environmental sustainability, themes such as air quality, water quality, and food quality were assigned.[4] For social sustainability, holistic wellbeing dimensions, such as physical, spiritual, emotional, and mental health, were selected,[108] and economic sustainability considers themes like healthcare costs, tourism impacts, and remediation costs.[109] Nodes under each pillar of sustainability represent key elements. Blue arrows indicate positive feedback, where an increase in one element increases another, while red arrows indicate negative feedback, where an increase in one element decreases another.

framing thus amplifies the urgency for more interdisciplinary, field-validated solutions to manage MNP pollution effectively.

A major research gap lies in the limited focus on NPs (Table 5). While studies on MPs are emerging, those on NPs remain scarce. This review identified only two eligible research articles addressing NPs, highlighting a substantial gap in the literature. In addition, the behavior, transport, and removal mechanisms of both MPs and NPs in various SWMEPMS are not well understood, particularly their interaction with different types of porous media and under varying environmental conditions, most especially for NPs, given their distinct properties, such as their small size and high surface area. These distinct properties of NPs may influence their fate and transport differently from MPs. Therefore, more targeted studies are needed to elucidate these dynamics. Notably, there is no single study on MNP removal by HFD, a trench-based SWMEPMS. Additionally, although several studies stated that nature-based engineered porous media such as biochar and activated carbon possess high efficiencies for MNP removal,[90,105,106] more studies using SWMEPMS are needed to verify this, especially at the field level.

The existing studies often employ varying experimental conditions, including differences in the types of MNPs, concentrations, and environmental conditions (Tables 3–5). This variability makes it challenging to compare results across studies and draw generalized conclusions. Hence, there is a pressing need for standardized methodologies and protocols for experimental setups, particle characterization, and quantification techniques. This standardization would facilitate more accurate cross-study comparisons and enable more robust meta-analyses. Also, while some studies have explored the impact of environmental conditions such as temperature, rainfall intensity, and freeze-thaw cycles, the comprehensive effects of these factors are not fully understood. For instance, the impact of UV radiation on the degradation of MNPs and their subsequent behavior in SWMEPMS has not been extensively studied. Similarly, the influence of seasonal variations and their effects on the long-term performance of SWMEPMS requires further investigation to optimize system design and maintenance practices. Additionally, since weathered MNPs tend to move more easily because the energy required to push them into the water decreases and the net attractive forces decrease or repulsive forces increase with engineered porous media surfaces, we join Gunther *et al.* in recommending that future research should therefore use weathered MNPs instead of pristine ones and consider changing weather conditions to predict MNP transport and removal in SWMEPMS.[84]

There is a generally notable lack of long-term studies assessing the performance and maintenance needs of SWMEPMS systems. Understanding how these systems evolve over time, including potential clogging, changes in media properties, and degradation of infrastructure, is crucial for developing sustainable maintenance practices. Long-term monitoring and performance evaluation studies are needed to provide insights into the durability and operational lifespan of these systems. For instance, Essien *et al.* attempted to assess and evaluate the hydrologic performance of a trench-based SWMEPMS for the first time using 55-year hourly rainfall records.[53] However, the study did not look at any specific stormwater pollutants, leaving a gap in our understanding of pollutant removal efficiency over time. Moreover, while the environmental benefits of SWMEPMS are well-documented, there is limited research on their economic viability and cost-effectiveness. Future studies should assess the cost-benefit aspects of these systems, considering factors such as construction, maintenance, and potential economic benefits from improved water quality and ecosystem health. In conclusion, addressing these knowledge gaps through comprehensive research will significantly advance the field of SWMEPMS, enabling the development of more efficient, effective, and sustainable stormwater management solutions for MNP remediation.

4 Conclusion

This review provides a systematic and comprehensive synthesis and in-depth analysis of the sources, transport, removal mechanisms, retention and removal characteristics of microplastics and nanoplastics (MNPs) within stormwater management engineered porous media systems (SWMEPMS). The findings underscore the critical role SWMEPMS can play in mitigating plastic pollution, with reported removal efficiencies reaching up to 100%, driven by mechanisms such as straining, entrapment, agglomeration, electrostatic interactions, and surface complexation. The effectiveness of SWMEPMS is largely governed by the physical and chemical properties of the porous media and MNPs. Notably, materials such as limestone and biochar exhibit superior retention capabilities compared to sand, owing to their enhanced adsorption properties and surface structures. Functional groups such as amino, carboxyl, hydroxyl, and carbonyl present on either MNPs or the engineered porous media play a significant role in enhancing retention.

Although the number of studies on the use of SWMEPMS for MNP removal increased notably between 2021 and 2023, the subsequent decline in 2024 and the limited publications so far in 2025 suggest that the research field is still developing rather than showing a sustained upward trend. This trend may reflect analytical and methodological challenges in quantifying MNPs or scaling laboratory findings to field conditions or *vice versa*.

Operational and technical performance remains a critical consideration. Environmental variables, such as rainfall intensity, antecedent dry periods, and stormwater chemistry (*e.g.*, ionic strength, pH, and dissolved organic matter), strongly influence particle–media interactions and system efficiency. These factors can affect MNP transport in stormwater runoff, alter zeta potential, and either enhance or hinder MNP retention within SWMEPMS.

A key insight from the review is the predominance of tire wear particles (TWPs) in stormwater, posing distinct challenges due to their diverse physical and chemical complexity. While SWMEPMS are effective in removing larger microplastics (MPs), including TWPs, the removal of smaller plastic particles, especially nanoplastics (NPs), remains challenging, particularly under high flow conditions or in systems with smoother engineered porous media surfaces. Furthermore, the review identifies several critical knowledge gaps, including the lack of standardized quantification methods, limited understanding of the long-term behavior of MNPs under variable environmental conditions, and minimal research on NP removal. Most importantly, to the best of our knowledge, no study has yet explored MNP removal using certain SWMEPMS types, such as highway filter drains (HFDs). Addressing these gaps through future research is essential for optimizing the design and operation of SWMEPMS, thereby enhancing their effectiveness in MNP removal and contributing to more sustainable stormwater management practices. Such advancements will also contribute toward achieving Sustainable Development Goals (SDGs), particularly SDGs 6, 11, 13, and 14.

Conflicts of interest

There are no conflicts to declare.

Data availability

All papers analyzed in this review are previously published and publicly available. Relevant datasets and references are cited throughout the manuscript.

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