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Review

Permeable pavement systems for microplastic mitigation: Critical insights on transport, retention, detection and removal efficiency

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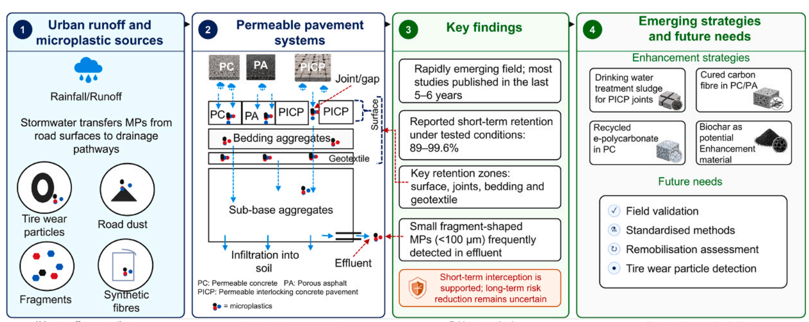
HIGHLIGHTS

- Microplastic retention by permeable pavements is an emerging research field.
- Short-term retention efficiencies under tested conditions ranged from 89% to 99.6%.
- Fine microplastic fragments (<100 μm) are frequently detected in effluent.
- Microplastics accumulate mainly in surface, joints, bedding and geotextile layers.
- Long-term field validation and remobilisation studies are urgently needed.

GRAPHICAL ABSTRACT



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ABSTRACT

Microplastics (MPs) in urban stormwater are emerging contaminants of increasing concern due to their persistence, mobility, and potential impacts on ecosystems and human health. Permeable pavement systems (PPS) have gained attention as stormwater control measures capable of intercepting MPs; however, their long-term performance and associated uncertainties remain poorly understood. This paper synthesises current evidence on MP transport, retention, detection, and removal in PPS based on twenty-eight peer-reviewed studies published between 2000 and May 2026. The evidence indicates a rapidly emerging field, with most studies published during the past six years and annual output peaking in 2025. Reported short-term MP retention efficiencies range from 89% to 99.6% under controlled and field conditions. However, meaningful comparison among studies is constrained by substantial variation in pavement configurations, hydraulic loading, MP characteristics, and analytical methodology. Retention occurs predominantly within surfaces, joints, bedding, and geotextile layers, whereas fragment-shaped MPs (<100 μm) are most frequently detected in effluent. Emerging design innovations, including drinking water treatment sludge, cured carbon fibres, recycled e-polycarbonate aggregates, and tyre- or plastic-derived materials, show potential for enhancing retention and hydraulic or mechanical performance. Nevertheless, their long-term durability, remobilisation potential, secondary MP generation, and life-cycle implications remain largely unresolved. Overall, current evidence provides stronger support for short-term MP interception than sustained environmental risk reduction. Future research should prioritise harmonised

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monitoring and analytical protocols, long-term field validation, improved detection of tyre wear particles, mass-balance assessment, and evaluation of MP remobilisation under realistic hydraulic, climatic, and maintenance conditions to strengthen confidence in PPS as sustainable stormwater treatment technologies.

1. Introduction

Stormwater from urban areas contains several contaminants such as suspended solids, nutrients, Pb, Zn, phosphorus, and nitrogen [1–3] and emerging ones include antibiotic resistance genes (ARGs), per- and polyfluoroalkyl substances (PFAS), microplastics (MPs), tyre wear particles (TWPs), and thermal pollution [4]. These emerging contaminants differ from traditional ones in that they arise primarily from modern materials and processes and pose unique risks. They collectively pose significant threats to human and ecosystem health [5–7]. Among these, MPs (including TWPs) have received the most attention in the context of Low Impact Development (LID) and Sustainable Drainage System (SuDS) [8,9] due to their growing concern globally [4,10].

Plastic production has increased exponentially on a global scale, reaching more than 400 megatons in 2022, with a projected increase of approximately 12 billion tons by 2050 [11,12]. Only about 9% of these plastic wastes are recycled; the rest either end up in landfills or are mismanaged, which subsequently enters the environment [13,14]. Over time, these plastics degrade into small particles known as MPs, commonly defined as plastic particles smaller than 5000 μm, with lower size ranges varying across studies depending on the definition and use [12,13,15]. Main sources include plastic litter, atmospheric deposition, synthetic turf and carpeting, paints, building material abrasion, textile fibres, tear of tyre and road pavements, and road dust [16–18]. During rain events, these particles are washed off from roads, sidewalks, parking lots, and other impervious surfaces and mobilised in stormwater runoff, which enters sewers or permeable pavement installations [19,20]. Given the prevalence of MPs in urban areas, exacerbated by climate change, urbanisation and more hard surfaces, conventional end-of-pipe drainage systems alone are ineffective in managing stormwater pollutants including MPs and TWPs [21,22]. Sustainable drainage approaches are gradually supplementing conventional drainage systems to mitigate these pollutants and their impacts [21].

Sustainable Drainage Systems, including bioretention cells, bioswales, rain gardens, green roofs, infiltration trenches, and permeable pavements, are designed to serve two major functions: to control stormwater runoff quantity and quality, with the aim of mitigating flood risk and improving stormwater quality [21,23,24]. This approach mimics natural processes that slow and retain stormwater runoff through infiltration, retention, storage, and filtration of pollutants. Permeable pavement systems (PPS), as a component of SuDS, have been widely studied for controlling stormwater pollutants at the source [1,25]. PPS are designed and implemented with different layers composed of permeable materials including the surface, bedding/base course, geotextile, and sub-base. During storm events, rainwater and runoff pass through the layers, and exfiltration from the system is controlled based on the system design (Type A - total infiltration, Type B - partial infiltration, or Type C - no infiltration) [23]. PPS are comprised of two main surface designs: (i) monolithic (e.g. permeable concrete (PC), clogging resistant permeable concrete (CRP, also known as Kiacrete), porous asphalt (PA); and (ii) and modular surfaces (e.g. permeable interlocking concrete pavement (PICP), concrete grid pavement (CGP), plastic grid pavement (PGP) [26–28]. Due to their distinctive design, permeable pavements, unlike conventional impermeable concrete or asphalt, facilitate infiltration and can remove a significant proportion of pollutants from rainfall and runoff through filtration, absorption-desorption, and biological processes [29,30]. Several studies have confirmed the capacity of permeable pavements in removing pollutants (sediments, suspended solids, heavy metals) from stormwater runoff [2,31]. Recent studies highlight the potential of permeable pavements for mitigating MPs [17,20,32]. Kong et al. [20] monitored a field-scale LID facility with a permeable pavement road and found that the permeable pavement captured nearly 98% of MPs. Similarly, García-Haba et al. [17] demonstrated high retention efficiencies (>90%) for both MPs and TWPs in PICP and PC under controlled laboratory study. In their experiments, MPs were found to accumulate primarily on the pavement surface and within the geotextile layer, with very few particles escaping to the effluent. These findings indicate that PPS can serve as a sink for these contaminants, which would otherwise enter stormwater sewers and subsequently watercourses. These findings are corroborated by Rasmussen et al. [32], who found that PA can retain a substantial portion of TWPs generated by roads and parking lots, suggesting that PA can play a significant role in their retention.

While permeable pavements have demonstrated high short-term retention efficiency, the unique properties of MPs, such as small size, lower density, hydrophobicity, and surface properties, may pose challenges distinct from those posed by traditional stormwater pollutants [33]. Understanding their interaction with pavement media is essential to ensure long-term effectiveness. Furthermore, as cities face growing pressures from polluted runoff, climate extremes, and the need to achieve sustainable development goals (SDGs), assessing the efficacy and limitations of permeable pavements for MP mitigation is both timely and critical. Previous reviews have largely treated PPS in one of two ways: either as a component of broader green infrastructure (GI), SuDS, or engineered stormwater management systems for MP mitigation [8,9,34,35], or as a treatment system for traditional contaminants [36]. These reviews lack detailed, focused synthesis that provides an understanding of transport and retention mechanisms, retention/removal efficiencies, and the challenges of MP mitigation by PPS. This study presents a detailed synthesis focusing on MP mitigation through PPS, offering insights into their transport, retention mechanisms, detection techniques, and retention efficiencies.

2. Data sources and methods

The study conducted a systematic literature review following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) protocol [37]. The literature search focused on peer-reviewed English-language studies published between 1 January 2000 and 31 May 2026. Scopus and Web of Science (WoS) were used as the main databases due to their extensive coverage of high-quality scientific literature [37,38]. To reduce database-related selection bias, equivalent keyword groups and Boolean operators were applied across both databases, with only syntax-specific adaptation. Searches were conducted using the TITLE-ABS-KEY field in Scopus, and the title (TI), abstract (AB), and author keyword (AK) fields in WoS. The search strategy combined terms related to MPs, including TWPs, with permeable pavement technologies and broader stormwater management concepts, such as LID, SuDS, Green Infrastructure (GI), Nature-based Solutions (NbS), as follows: (microplastic* OR "tyre wear particle*" OR "tyre wear particle*" OR "road wear particle*" OR "tyre and road wear particle*" OR "tyre and road wear particle*") AND ("permeable pavement*" OR "pervious pavement*" OR "porous pavement*" OR "porous asphalt" OR "pervious concrete" OR "permeable concrete "OR "permeable interlocking concrete pavement*" OR "concrete grid pavement*" OR "plastic grid pavement*" OR "porous material*") AND ("low impact development" OR LID OR SuDS OR "sustainable drainage system*"OR "green infrastructure "OR "nature-based solution*" OR "stormwater control measure*"). Google Scholar was used as a supplementary source to identify additional relevant studies not captured by the primary databases using the same search concepts. The complete database-specific search strings are provided in the Supplementary Material (see Table S1).

The inclusion and exclusion criteria were based on predefined criteria (see Supplementary Material, Table S2) and an examination of the titles, abstracts, and keywords returned by each search query. Given the interdisciplinary nature of the topic, studies on MPs in unrelated contexts, such as wastewater treatment, marine systems, or natural water bodies with no connection to PPS, SuDS, or stormwater runoff, were excluded. Studies were included where they investigated MP or TWP transport, retention/removal, or breakthrough in PPS. In addition, selected studies were included where they examined permeable pavement materials incorporating tyre-derived or plastic-derived components, or directly assessed MP release from pavement materials, as these studies provide relevant evidence on material innovation and potential secondary MP generation. Conventional impermeable pavement studies were excluded unless they directly evaluated MP release from pavement materials and were used as supporting studies. Articles published before 2000 were excluded because research on permeable pavements advanced significantly around the twenty-first century, particularly with the growing interest in SuDS, low-impact development and emerging pollutant mitigation [39,40]. Following screening and eligibility assessment, twenty-eight studies were included in the final review. Fig. 1 summarises the identification, screening, eligibility and inclusion process.

3. Results and discussion

A total of twenty-eight articles regarding MP mitigation through PPS were analysed for this review (see Table S3). Articles were assessed within the following themes: evidence base and characteristics of included studies (temporal distribution, PPS types, MP size, shapes and polymer types), MP inputs to PPS, detection and analytical challenges in PPS, transport, retention/removal efficiency in PPS, and future research directions.

3.1. Evidence base and characteristics of included studies

3.1.1. Temporal distribution

Research on MP mitigation by PPS is a relatively recent and rapidly expanding field, with most studies published after 2020, indicating that the potential role of PPS in MP control received little or no attention previously. Publication output increased steadily between 2020 and 2022, followed by a marked rise in 2023. Although publication output declined in 2024, research activity intensified again in 2025, reaching the peak annual output (see Fig. 2). This growth reflects increasing concern over MPs/TWPs, as pervasive urban runoff contaminants, and the growing interest in nature- or SuDS-based mitigation strategies such as PPS [5,10]. Advances in analytical techniques, notably micro-Fourier Transform Infrared imaging and pyrolysis gas chromatography-mass spectrometry, have further facilitated the detection, characterisation and quantification of MPs in PPS, enabling more detailed investigations of their transport and retention processes [32,41]. Despite this rapid growth, the evidence base remains limited, highlighting the need for further research to strengthen understanding of long-term retention, remobilisation, and field-scale performance of PPS.

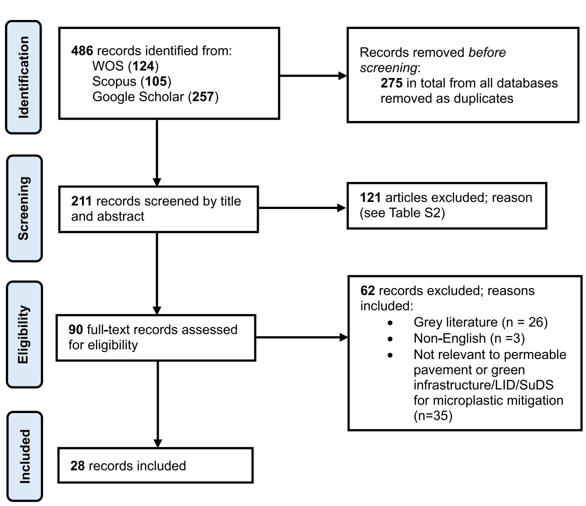

Fig. 1. Flow diagram of the literature search strategy for MP mitigation by permeable pavements. The figure outlines the number of records identified, screened, and ultimately included in the review.

3.1.2. Types of permeable pavements

The review indicates that a range of permeable pavements have been investigated for MP mitigation. Fig. 3 presents the distribution of studies by permeable pavement type, showing that PC has been investigated the most, followed by PICP and PA. Some studies also assessed combinations of pavement types, such as PICP and PC, PC and PA. Overall, PC and PICP have emerged as the most studied permeable pavement types for MP mitigation. Although the reasons for this trend are not fully clear, it reflects their widespread implementation [42] and well-documented effectiveness in removing conventional stormwater contaminants [43].

3.1.3. Microplastic size, shapes and polymer types reported in PPS studies

Fig. 4 summarises the MP size ranges investigated or detected in PPS studies. The size ranges reported in each study were grouped into five categories: 10–40 µm, 50–100 µm, 100–500 µm, 500–1000 µm, and > 1000 µm. The 50–100 µm and 100–500 µm classes were reported most frequently, while particles larger than 1000 µm were less commonly reported across the review studies. Several studies [17,19,20,48] reported high short-term MP retention, particularly for larger MPs. However, MPs below 100 µm remain more challenging to retain within permeable pavement layers. These finer MPs may migrate through the pavement layers and have been detected in effluent [17,20]. This behaviour may reflect the greater mobility of finer particles under infiltrating flow, whereas larger particles are more likely to be retained by sedimentation, filtration, straining, or interception within pore spaces, joints, bedding aggregates, or geotextile interfaces [17,34,48]. Further research is needed to quantify size-specific retention and breakthrough using harmonised size classifications.

Regarding MP morphology, fragment-shaped MPs were dominant in permeable pavement effluent (see Fig. 5), whereas fibres were less frequently observed. Fragments originating from decomposed or disintegrated plastic [44] are small enough to pass through pavement layers with water, whereas longer, thread-like fibres [45] are more likely to become entangled and retained in the pores and joints of the upper layers.

Fig. 6 summarises the MP polymer types investigated or detected in

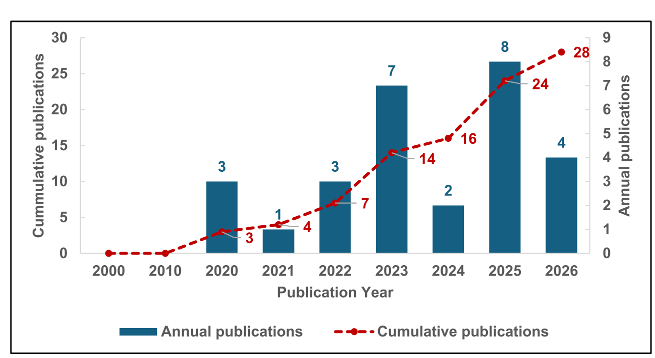

Fig. 2. Distribution of published articles focused on PPS for MP mitigation between the review period (2000 and 2026).

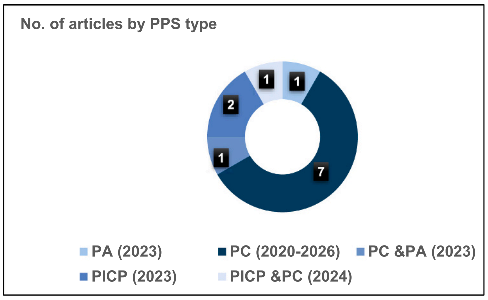

Fig. 3. Distribution of published articles based on PPS types.

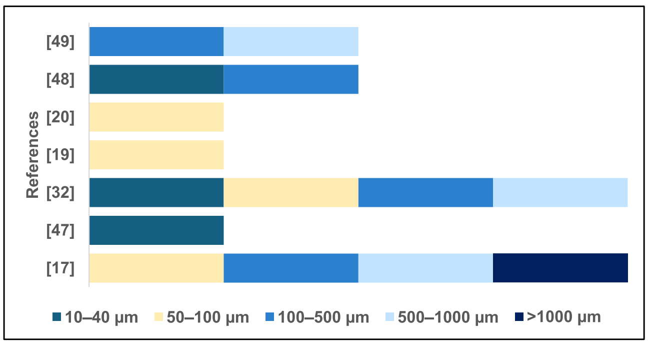

Fig. 4. Reported MP sizes investigated or detected in PPS layers or samples across the reviewed studies.

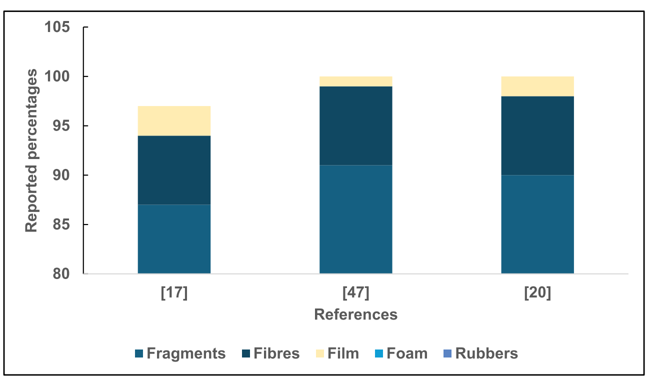

Fig. 5. Prevalent MP shapes detected in PPS layers/samples reported across the studies.

PPS-related samples. Across the reviewed studies, common polymers included polypropylene (PP), polyethylene terephthalate (PET), polyethylene (PE), polyvinyl chloride (PVC), polyamide (PA), polyester, and other synthetic polymers. Kong et al. [20] and García-Haba et al. [17] identified PE and PP, respectively, as dominant polymers in specific permeable pavement samples, while PP was reported across several studies. PP was consistently detected across most studies, reflecting its widespread industrial and residential use [45,46]. TWPs were also reported in road dust, sediment, and runoff-related samples, with some studies identifying tyre-related particles as an important fraction of traffic-affected urban samples [17,31]. However, current evidence on TWPs remains limited, as only a small number of studies have specifically quantified tyre-related particles and their retention or breakthrough in PPS. Further studies are needed to improve the detection of TWPs and assess their transport and retention behaviour across different PPS configurations.

3.2. Microplastic inputs to permeable pavement systems

Microplastics entering PPS originate from multiple sources and pathways (see Fig. 7): direct rainfall and atmospheric deposition, road and car-park runoff, TWPs, tyre-road wear particles (TRWPs), pavement wear, road dust, synthetic fibres, fragments, films and common polymers such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET) and polyvinyl chloride (PVC) [16–20,32]. Tyre wear particles are particularly important in road-related stormwater as they are generated by tyre abrasion and can combine with mineral road dust to form TRWPs [19,50]. Rasmussen et al. [32] reported TWPs as the dominant particle type in porous asphalt road and parking-lot dust, while García-Haba et al. [17] found TWPs in both road dust/sediment and stormwater runoff. The limited number of studies focused specifically on TWP retention reflects the emerging nature of the field and the analytical difficulty of distinguishing TWPs from other carbon-rich or rubber-like particles [32].

3.3. Microplastic detection and analytical challenges in PPS

Detection of MPs in PPS is strongly influenced by the type of sample matrix analysed. Current studies have examined a range of matrices, including road dust, retained sediments, jointing material, bedding aggregates, geotextiles, sub-base material, direct rainfall, synthetic stormwater, infiltrated water and outlet effluent [17,19,20,32,48]. These matrices differ in organic matter content, mineral composition, particle-size distribution, hydraulic exposure and contamination risk, all of which may affect extraction efficiency, polymer confirmation and the reliability of reported retention or removal efficiencies.

The sample matrix also influences how study findings should be interpreted. For example, road-dust or surface samples collected from permeable pavement sites may indicate MP particle accumulation at or near the pavement surface, but they may not capture particles retained in underlying layers (e.g., bedding, geotextile, or sub-base). In-situ monitoring of rainfall, inflow and outlet effluent can provide more direct evidence of inflow-outflow differences, but depends heavily on storm occurrence, rainfall volume and the ability to collect representative samples across multiple events. In contrast, laboratory-scale dosing experiments allow controlled assessment of particle size, density, polymer type and loading, but may simplify real stormwater conditions and field-scale variability. Reported retention efficiencies must thus be interpreted in view of these methodological differences. Fig. 8 provides an overview of the general workflow for MP analysis in PPS, which encompasses various sample matrices. This process includes stages from sample collection and preparation to the identification and classification of MPs using different analytical techniques.

3.3.1. Sample matrices and collection methods

Sampling approaches for assessing MP removal by permeable pavement vary across studies. Some studies rely on field sampling of road dust or stormwater runoff from permeable pavement sites or other adjacent sediment-laden impervious surfaces. For example, Rasmussen et al. [32] collected ~700 kg of road dust from seven porous asphalt roads using maintenance and cleaning truck for MP analysis. The challenge with this approach is that it cannot determine the depth of MP migration within pavement layers and may underestimate total retention by missing particles trapped in deeper layers, compared with full-scale in-situ monitoring. In contrast, Kong et al. [20] monitored both direct rainfall and effluent from permeable pavement drainage outlets. This in-situ approach allows direct tracking of MPs in rainwater and those entering and leaving the permeable pavement installations under realistic conditions. A key limitation of this approach is the difficulty in obtaining sufficient rainfall volume for analysis, as sampling depends on the occurrence and magnitude of rainfall events. Consequently, multiple rain events are often combined to obtain adequate sample volumes (e.g. 1 litre) for analysis. Despite their limitations in replicating field

Polymer types										Sources
PP	PVOH	PVC	POLYESTER	PET	PE	PA	LDPE	MRs	TWPs	
1	1	1	1	1	0	0	0	1	1	[17]
1	1	1	1	1	0	0	0	0	0	[47]
1	0	0	1	0	1	1	0	1	1	[32]
0	0	0	0	0	0	0	0	0	1	[19]
1	0	0	0	1	1	1	0	0	0	[20]
0	0	0	0	1	1	0	0	0	0	[48]
0	0	0	0	0	0	0	1	1	0	[49]

Fig. 6. Common MP polymer types investigated/detected in PPS samples, as reported across studies (1 = present; 0 = absent).

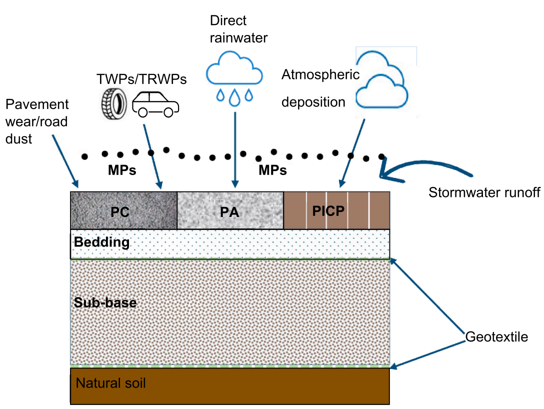

Fig. 7. Pathways of MPs into permeable pavement system.

conditions, controlled lab-scale studies have been instrumental in advancing understanding of MP retention in permeable pavements, beyond what field investigations could offer. In such studies, matrices including road dust, sediments, stormwater runoff, direct rainwater, or synthetic stormwater [17,20,48] are applied to physical models of permeable pavement, enabling controlled sampling and analysis. The innovation in controlled lab-scale sampling lies in the flexibility to analyse MPs for different scenarios and at specific or entire pavement depths. This detailed analysis could reveal where and how deep into the pavement layers MPs migrate and accumulate [17]. A combined approach that integrates laboratory experiments with field monitoring would provide a more robust assessment of MP retention and breakthrough in PPS. It is, however, important to cover adequate and more representative sampling. For example, where possible, more field sampling must be undertaken (as in Kong et al. [20]), in particular, should capture multiple rainfall events to accurately quantify MP inflows and outflows. This can be achieved using automated stormwater samplers, as demonstrated by Garcia-Haba et al. [17], which can be adapted to suit typical rainfall patterns of the site to be sampled.

3.3.2. Sample processing methods

Following collection, samples require further preparation and processing (see Table 1) to facilitate MP identification. Common steps include sieving, chemical digestion, density separation, and filtration [51]. However, sample processing methods varied widely across studies and largely depended on the study design (in-situ monitoring, field sampling, laboratory experiments). Only one study [48], which analysed real effluent samples, used sieving as initial treatment to remove large

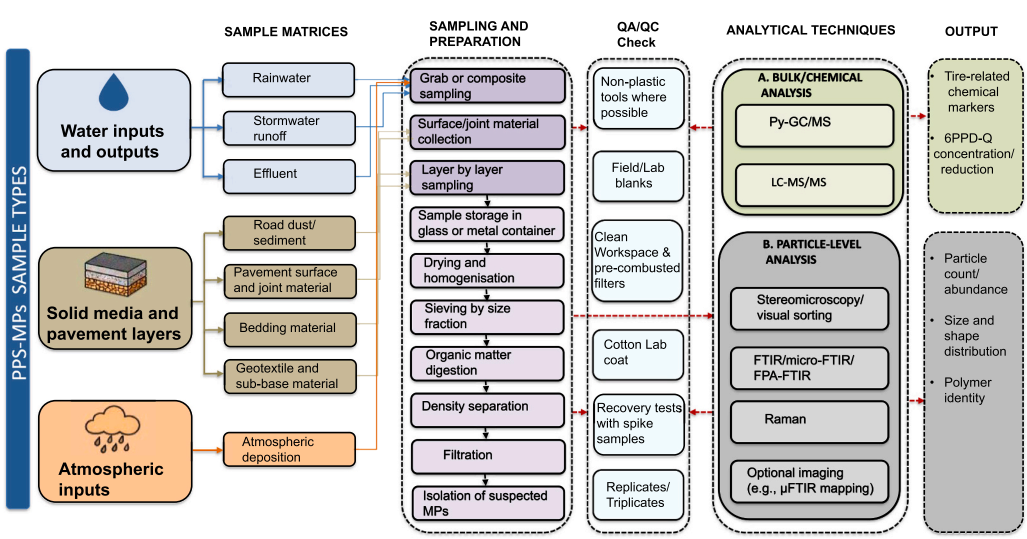

Fig. 8. Summary of the general processes involved in MP analysis in PPS. The framework summarises sample matrices, preparation steps, QA/QC procedures, analytical techniques, and outputs relevant to microplastic detection in PPS [17,19,20,32,48].

Table 1
Summary of sample processing methods used across studies for MP analysis in PPS.

Method	Sample type processed	Pre-treatment	Density separation	Filtration	References
Field sampling	Road dust/ sediment	Sedimentation (48 h), filtration (10 µm stainless steel filters), ultrasonication, re-sedimentation (1 h), oven-drying (50 °C), homogenization (30 g) with mortar and SPT (1.9 g/cm3), SDS treatment (5%, 50 °C, 48 h), enzymatic treatment (protease in 0.2 M tris buffer, (pH 8.2) cellulase & viscozyme in acetate buffer, pH 4.8), Fenton's reaction (145 ml H_2O_2 + 62 ml $FeSO_4$, pH 3, 0.1 M NaOH)	1st separation - SPT solution (1.9 g/cm^3); 30 min air compression; 24 h settlement; 2nd separation - float-fraction concentrated in 10 ml, 50% C_2H_5OH		[32]
Lab-scale experiment	Infiltrated water, retained sediments	For sediment samples: 1st digestion - 150 ml acidic oxidation using H_2SO_4:H_2O_2 (1:1) added gradually (10 ml every 30 min) for 72 h; 2nd digestion - Fenton reagent (H_2O_2 + Fe^{2+}) under ice bath (<40 °C), mixed at 100 rpm for 5 days, then oven-dried at 45 °C for 4 days.	NaCl (322 g/L; 1.2 g/cm^3), stirred and settled for 24 h. Extraction repeated 4 times; $NaHCO_3$ added in 4th extraction cycle to aid flotation of dense MPs via CO2 bubbles	Glass fibre filters, 1.2 µm pore size, 47 mm diameter (for both water matrix and final extraction of retained sediments).	[17]
In-situ monitoring	Rainwater, infiltrated water	300 µm stainless steel mesh sieve to remove large particles (e.g. rocks, leaves); chemical digestion with 30% H_2O_2, 100 ml of water sample at 60 °C for 24 h	15 g of $ZnCl_2$ added to 150 ml sample; allowed to settle for 48 h	Anodisc™25 filters, 0.2 µm pore size, 25 mm diameter	[20]
Lab-scale experiment + numerical modelling	Infiltrated water			Anodisc™25 filters (0.2 µm, 25 mm diameter)	[48]
Controlled field experiment	Infiltrated water from pavement	Samples cleaned with MilliQ water, methanol, ethyl acetate, etc.; stored at 4 °C and −20 °C	$ZnCl_2$ (with density 1.6–1.7 g/cm^3) to separate light and heavy MPs	Glass fibre filters, 47 mm diameter	[19]
Field sampling	Infiltrated water from pavement outlet	Added 10% isopropyl alcohol, sieve through 106–300 µm, 300–500 µm, 500–1000 µm	1st separation CaCl2 (1.4 g/cm3), 0.1862 g of FeSO4·7H2O and 162 ml 30% H_2O_2 at 60 °C for 2 h; 2nd separation $ZnCl_2$ 1.7 g/cm^3) for 24–48 h		[52]

particles such as rocks and leaves. Rasmussen et al. [32] analysed road dust by allowing samples to settle in a sedimentation tank, removing

Table 2
Summary of MP detection techniques used across the reviewed studies.

Microplastic Identification technique	Merits	Demerits	Detection limit	References
Focal plane array-Fourier transform infrared (FPA-FTIR) spectroscopy	Non-destructive testing; enables hyperspectral imaging, good for polymer identification	Cannot detect TWP due to interference from carbon black; large sample requirement; time intensive	5.5 µm	[32]
Py-GC/MS (Pyrolysis gas chromatography–mass spectrometry)	Detects TWPs, high chemical specificity and sensitivity	Destructive; complex and time-consuming, requires standard calibration		
Stereomicroscope	fast visual screening; support the selection of suspected MPs for further analysis	Cannot identify polymer type; can be subjective; limited to visible particles	10–20 µm	[17]
Raman Spectroscopy	Identifies polymers; high precision; allows detection of weathered and composite MPs using libraries (Open Specy, SLoPP)	High cost of equipment; fluorescent interference	2.47 cm^{-1} spectral; 162–1886 cm^{-1}spectral range	
Hot needle test	Simple and low-cost; can help confirm the behaviour of thermoplastics	Cannot identify polymers type or degraded plastics; used only to estimate morphology of MPs		
ImageJ (public domain image processing software)	Standardised image analysis tool; allows classification of MPs by size	Estimate MPs size only; relies heavily on accurate visual detection and clear image	10–5000 µm	
micro-FTIR spectroscopy	Identifies polymers; non-destructive testing; based on unique IR (infrared) spectra	Limited by particle size and surface characteristics; time-consuming, requires dry and clean samples	20 µm	[20]
Micro-FTIR with chemical image mapping	High recovery rates (89–92%); correlates well with reference spectra	Time-consuming; effective only for polymer types with detectable IR peaks		[48]
Agilent 1290 chromatograph; Agilent 6460 Triple Quadrupole mass spectrometry (LC-MS/MS)	Highly sensitive - detect low concentrations of tyre-associated chemicals like 6PPD-Q; very reliable and can produce multiple analysis in one run	Costly – equipment, maintenance and calibration; require specialist, cannot provide information on size, shape, polymer type		[19]
Visual method (stereomicroscope)	Rapid screening, quantifies MPs by shape and colour	Less accurate, can be subjective, struggles to confirm polymer types		[52]
Micro-FTIR (Hyperion 3000 & Tensor II spectrometer)	Non-destructive testing, high resolution spectrum, detailed quantification and classification of MPs	Time-consuming, require expert assistance, expensive		
Raman Spectroscopy	Identifies polymers; high spectral precision; complements FTIR analysis	High cost of equipment; fluorescent interference		

excess water by filtration, and oven-drying the remaining particles. Chemical digestion is then used to remove organic matter (all non-plastic particles) and other impurities from the samples using chemicals or enzymatic treatment. Reported methods include treatments with Sodium polytungstate (SPT), Sodium dodecyl sulphate (SDS), enzymatic digestion, combined enzymatic-Fenton digestion [32], hydrogen peroxide (H_2O_2) [17,20,32], Fenton reagents [17], and isopropyl alcohol [52]. After chemical digestion, samples typically undergo density separation. This process is commonly used to isolate MPs based on the density difference between MPs and associated particles (e.g., silt and sand). Various salt solutions have been used for this purpose, including: SPT (1.9 g/cm^3) and C_2H_5OH [32]; NaCl (1.2 g/cm^3) and $NaHCO_3$ [17]; $ZnCl_2$ (1.6–1.7 g/cm^3) [19,20,52] and $CaCl_2$ (1.4 g/cm^3) [52]. Zinc chloride ($ZnCl_2$) is the most used solution (see Table 1). This phenomenon may be attributed to the assertion that ZnCl2 yields superior recovery outcomes compared with NaCl, especially for dense polymers such as PVC and PET [53]. However, $ZnCl_2$ can be toxic and costly compared with NaCl or $CaCl_2$ [54], prompting some studies to adopt alternatives. For example, Garcia-Haba et al. [17] used NaCl followed by $NaHCO_3$ to aid denser MPs to float through CO_2 bubbles, while Rasmussen et al. [32] used the higher-density SPT solution to extract TWPs. Following density separation, samples are typically allowed to settle for 24–48 hrs and then filtered, enabling subsequent classification of MPs by size, shape, and polymer type using various detection techniques (see Tables 2 and 3).

3.3.3. Quality assurance/control for MP analysis in PPS

Given the ubiquity of MPs, most studies implemented a range of additional steps to ensure the quality and credibility of the reported performance of permeable pavement in retaining MPs. Non-plastic equipment, typically aluminium, stainless steel, or glass, was widely used to minimise contamination [8,17,32]. For example, Rasmussen et al. [32] and García-Haba et al. [17] used metal or glass containers and pre-heated filters at 500 °C to remove any residual plastic before use. A common step included thorough rinsing of equipment, and the use of cotton laboratory coats to avoid unintended shedding of MPs [17]. Such practices align with the broader investigation of MPs beyond permeable pavement. Shruti et al. [51] suggested control measures to reduce air and to use non-plastic equipment to avoid introducing additional MPs into the samples under investigation. Other studies also analysed blank samples to detect procedural contamination [19,20,32]. Mitchell and Jayakaran [19], for example, analysed field blanks for each pavement in their field experiment using deionised water processed identically to pavement effluent samples. This procedure was done to capture potential MPs introduced during sampling. Similar procedures were performed by Kong et al. [20] and Rasmussen et al. [32].

In addition to the above control measures, some studies conducted validation tests to assess the reliability of detection techniques [19,48]. For example, Kong et al. [48] spiked clean water with known quantities of PE and PET and performed entire sample processing and micro-FTIR analysis on the samples. They recovered approximately 90% of PE and PET, indicating the reliability of the detection technique. Mitchell and Jayakaran [19] also ran recovery tests to validate analysis of 6PPDQ chemicals. They applied water samples with known concentrations of 6PPDQ, and the solution was analysed to determine whether laboratory analysis could accurately detect 6PPDQ chemicals. The results revealed that 4 out of the 5 samples were considered acceptable, validating the sample detection technique. However, the robustness of these protocols allows for a distinction in the credibility of reported removal efficiencies across the reviewed literature. For instance, some studies that integrated both procedural blanks and spiked recovery tests [19,48] provide high-confidence evidence, as they account for both external contamination and the analytical limits of the detection systems. In contrast, studies that relied solely on basic contamination controls or simple visual quantification without formal recovery validation should be interpreted as indicative evidence (see Table 4). Furthermore, most validation experiments considered a limited range of polymers and regular shapes, which may not be representative of real-world samples. An approach that considers a variety of polymer types, shapes, and sizes to mimic the diversity of real samples is essential to elevate the credibility of current findings.

Table 3
Expected effect of key factors influencing MP transport and retention in PPS.

Factor	Expected effect on transport and retention	Comments	References
Particle-size/pore-throat ratio	Larger particles relative to pore throats, joints or geotextile openings are more likely to be retained by straining, interception or surface accumulation.	Size alone does not control transport; pore connectivity, shape, density and hydraulic loading can offset size-related retention.	[17,34,48]
Density	Density may influence settling, buoyancy and mobility through pavement layers.	Higher-density particles may still migrate where pore pathways and hydraulic conditions favour transport.	[48,59]
Shape	Fibres may entangle, while irregular particles may be intercepted or trapped within pores and joints.	Small fragments may remain mobile and pass through pore networks, especially when aligned with flow.	[17,34]
Surface properties	Surface charge, roughness, hydrophobicity and weathering may influence attachment to aggregates, sediments or biofilms.	Direct PPS evidence remains limited; the current interpretation is partly inferred from studies of porous media.	[34]
Pore structure	Smaller or more tortuous pores can increase filtration and interception.	Pore narrowing may also increase clogging and alter flow pathways.	[26,34,48, 60,61]
Hydraulic loading	Higher rainfall intensity and flow velocity can increase mobilisation and reduce retention.	Evidence remains limited; however, reduced retention with increasing rainfall intensity has been reported.	[41]

3.3.4. Microplastic identification and characterisation in PPS

A range of techniques has been used to identify and characterise MPs in PPS, including visual inspection, stereomicroscopy, Fourier transform infrared spectroscopy, Raman spectroscopy, Py-GC/MS and other chemical analytical methods (see Table 2). The choice of technique depends strongly on the study design, sample matrix and target particle type. For example, studies that used known or artificially dosed particles relied mainly on visual or microscopic counting to estimate particle retention before and after filtration [19,48,49]. Studies involving road dust, real stormwater, retained sediments or effluent generally require confirmatory polymer identification because these matrices contain mineral particles, organic matter, tyre-derived particles and other non-plastic materials [17,20,32].

In controlled experiments in which known quantities and types of particles are introduced into the pavement system, simpler identification approaches may be appropriate for estimating retention under the tested conditions. Mitchell and Jayakaran [19], for example, applied a known dose of TWPs to permeable pavement installations and quantified retention by measuring particles captured in the effluent. Similarly, Trinh et al. [49] estimated MP retention in PC using microscopic counting before and after infiltration. These approaches can be useful where the input material is predefined, but they provide limited information on polymer diversity, weathered particles, unknown environmental particles and the behaviour of mixed MP assemblages.

In studies involving real environmental matrices (e.g. stormwater

Table 4
Reported MP retention/removal, and accumulation in PPS across reviewed studies.

Pavement Type/study scale	Particles tested/detected	Rainfall/ MP Loading	MP/TWP Confirmation Method	Detection Limit	QA/QC (Blank/ Recovery)	Polymer Identification	Reported Outcome	References
PC; Laboratory and modelling	40–112 µm; fragments, synthetic PE, PET	15–72 mm/h synthetic rainfall spiked with 10 mg of PE and PET	µm -FTIR chemical image mapping; OMNIC library matching	Not explicitly reported; target particles were 40 and 112 µm	Yes / Yes	Yes	> 90% retention for PE and PET	[48]
PICP; in-situ monitoring	PE, PP, PET, PS, PA, PVC; 50–100 µm, fragments dominant	Natural rainfall and outlet/infiltrated water	micro-FTIR chemical image mapping; OMNIC library matching; IR spectra checked for polymer confirmation	20 µm	Yes / Yes	Yes	approximately 98% MP retention	[20]
PICP, PC; Laboratory	MPs and TWPs; < 100–5000 µm; polymers included PP, PET, PVC, PVOH, HDPE; mainly fragments and fibres	32 mm/h simulated rainfall and real runoff; dry road dust/sediment applied to pavement surface	Stereomicroscope + Raman spectroscopy for polymer confirmation; geotextile particles assessed visually and by hot needle test	10–20 µm	Yes / Yes	Yes, except geotextile particles	89.0–99.6% overall MP retention	[17]
PC, PA; controlled field	Synthetic TWPs; 50 µm; 6PPD-Q	32 L/min simulated rainfall; 500 g of TWPs dry-deposited over pavement	Density separation/ image microscopy for TWPs and LC-MS/MS for tyre-associated chemicals including 6PPD-Q	N/A	Yes / Yes	No, for polymer-confirmed TWP identification; Yes, for tyre-associated chemical markers using LC-MS/MS	> 96% TWP retention; 52–100% 6PPD-Q mass reduction	[19]
PA; field sampling/ laboratory	TWPs and other MPs; 10–1000 µm	Road and parking-lot dust	FPA-FTIR for non-TWP MPs; Py-GC/MS for TWP	5.5 µm	Yes / No	Yes	105.02 mg/m^2 retained areal load for TWPs and 4.52 mg/m^2 for other MPs	[32]
PICP; Laboratory	fibres, fragments and pellets; PP, PVOH, polyester-epoxy, PVC, PET, ABS	32 mm/h simulated rainfall; real dust/ sediment applied at 5 g/ m^2/day	stereomicroscope + Raman spectroscopy	N/A	No / No	Yes	94.0% MP retention	[47]
PC; laboratory	LDPE-MPs and microrubbers; 105–841 µm	10 g/L of MP solution tested for 10 cycles	Mass-based filtration test	N/A			Improved retention compared with conventional PC	[49]
PC; in-situ monitoring and laboratory	fibres; polymers included PE, PP and PET	real urban exposure	Stereomicroscopy + Raman spectroscopy after oxidation and density separation	Size fractions: 425, 75 and 40 µm meshes	Yes / Yes	Yes	PC slabs accumulated 10,272 ± 5829 MPs/m^2	[67]

runoff, road dust), advanced spectroscopic or chemical confirmation is more crucial. Fourier transform infrared (FTIR) spectroscopy, including micro-FTIR and focal plane array-FTIR, has been widely used as it enables non-destructive polymer identification and can provide particle-level information on polymer type, size and shape [20,32,55]. Rasmussen et al. [32], for example, used FPA-FTIR to analyse road dust from permeable pavements, with a reported detection limit/resolution of 5.5 µm. However, FTIR-based methods can be less effective for TWPs due to interference from carbon black and the complex rubber matrix with spectral identification [32,56]. This limitation is important as TWPs are an important road-derived MP source in traffic-affected environments, and their under-detection may affect conclusions about which particle types are retained in or transported through PPS.

To address the limitations of spectroscopic methods for tyre-related particles, some studies have used bulk chemical techniques such as Pyrolysis gas chromatography–mass spectrometry (Py-GC/MS) [32]. Rasmussen et al. [32] combined FTIR with Py-GC/MS to detect characteristic pyrolysis products associated with TWPs, showing that tyre-related particles formed a substantial proportion of the sampled material. Similarly, LC-MS/MS has been used to analyse tyre-associated chemicals such as 6PPD-quinone in permeable pavement effluent [19]. These methods are valuable because they can identify tyre-related chemical markers that may be missed by visual or FTIR-based methods. However, they are usually destructive and generally do not provide particle-level information on size, shape, morphology or layer-specific distribution. Therefore, chemical methods can strengthen evidence on the presence of tyre-related materials, but they cannot fully explain particle transport pathways unless combined with particle-level techniques.

Raman spectroscopy and stereomicroscopy have also been applied in permeable pavement studies. García-Haba et al. [17] used stereomicroscopy to visually select suspected MPs, followed by Raman spectroscopy to confirm polymer identity using reference spectra. This combined approach provides stronger confirmation than visual identification alone and enables polymer-level interpretation of retained and transported particles. However, reliance on visual pre-selection may introduce observer bias and may overlook fine, irregular, weathered, or dark particles, including TWPs. In addition, where retained particles are not confirmed by spectroscopic techniques, reported retention patterns must be interpreted with caution, as morphology-based identification alone may misclassify non-plastic particles as MPs or fail to detect polymer-specific differences. These methodological differences may directly influence the interpretation of reported retention efficiencies. Reported retention efficiencies must be interpreted in view of the confirmation method used, the detection limit, the polymer identification approach, the use of blanks, and recovery tests (see Table 4).

Overall, a single analytical method may not fully characterise MP behaviour in PPS. Particle-level techniques such as stereomicroscopy, FTIR and Raman spectroscopy are useful for assessing particle size, shape, abundance and polymer identity, while bulk chemical techniques such as Py-GC/MS and LC-MS/MS are better suited to tyre-related markers and chemically complex materials. A combined approach could be more reliable, particularly where studies aim to quantify both general MP retention and TWP behaviour. Future studies should apply confirmatory methods across relevant pavement layers and effluent samples, report detection limits and recovery performance, and clearly distinguish between visually suspected particles, polymer-confirmed particles and chemically inferred tyre-related particles. This would improve the reproducibility of PPS-MP studies and strengthen confidence in reported retention/removal efficiencies.

3.4. Microplastic transport, retention/removal performance in PPS

Microplastic transport, retention and removal in PPS are governed by the combined influence of particle properties, pavement configuration and hydraulic conditions. Unlike conventional stormwater pollutants [1], MPs occur as fibres, fragments, films, particles and rubber-like materials, with wide variation in size, density, surface chemistry and morphology [34]. These characteristics influence whether particles are retained near the pavement surface, trapped within joints or pore networks, intercepted in bedding or geotextile layers, transported into the sub-base, or discharged through the outlet effluent [17,20,32,48].

Reported studies indicate that PPS can achieve high short-term retention under tested conditions, but the mechanisms responsible for this performance vary across pavement types and particle classes [17,19,20,32,48]. Therefore, retention or breakthrough must be interpreted along with particle-size/pore-throat ratio, density, shape, surface properties, pavement pore structure, degree of clogging, and hydraulic loading. A high overall retention value does not necessarily imply that all particle fractions are equally retained. Finer MPs have been detected in effluent even where overall retention efficiencies were high [17,20]. This indicates that total retention capacity and the composition of the particles that escape through the system should be evaluated separately.

The main retention mechanisms in PPS include straining, filtration, sedimentation, interception, entanglement and attachment to pavement media or retained sediments [17,34,48]. These are dependent on whether the system is a monolithic pavement, such as PC and PA, or a modular pavement, such as PICP. In PC/PA, flow is distributed through an interconnected pore network where most particles are intercepted in the surface, whereas in PICP, flow is concentrated through the joint aggregates, which is a key filtration zone [17,23,57]. These structural differences influence MP retention zones and the likelihood of fine-particle breakthrough.

3.4.1. Factors influencing transport and retention in PPS

The behaviour of MPs in PPS is governed by interactions among physical, chemical, and hydraulic factors that may affect their transport and retention (see Table 4). Key physical factors include particle size relative to pore-throat or joint openings, polymer density, particle shape, surface roughness, and the geometry of the pavement pore network. Chemical factors include surface charge, hydrophobicity, pH and ionic strength, which may influence attachment to aggregates, sediments, organic matter or biofilm-coated surfaces. Hydraulic factors include rainfall intensity, flow velocity, residence time, antecedent moisture conditions and the development of preferential flow pathways.

The particle-size-to-pore-throat ratio is a major factor in mechanical retention. Particles that are large relative to the available pore throats, joint openings or geotextile apertures are more likely to be retained by straining, interception or surface accumulation [34]. This mechanism is particularly relevant in the upper layers of PPS, where pavement pores, joint aggregates, bedding material and geotextiles may act as filtration zones [17,34]. However, particle size alone does not determine transport behaviour. Smaller particles may pass through pores more readily, but they may also be retained by attachment to sediments, mineral surfaces, geotextiles or biofilms. Conversely, larger particles may migrate if the pore pathways, hydraulic forces, or particle morphology favour transport [34,48].

Density also influences mobility, but its role depends on the surrounding hydraulic and pore conditions. For example, denser particles may settle more readily under low-flow conditions, while less dense particles may remain suspended or be transported with infiltrating water [34,58]. However, Kong et al. [48] found that less-dense PET was retained more effectively than denser PET in permeable pavement blocks, with PET showing greater mobility through the pavement matrix. This suggests that density may interact with other factors such as pore connectivity, polymer type, surface properties, or rainfall intensity. Similar findings from porous media studies also indicate that denser particles can migrate deeper where flow pathways and media structure allow transport [59].

Particle shape further influences retention and breakthrough. Fibres may become entangled within pores or joints, while irregular fragments may be intercepted or trapped depending on their orientation and contact with the media [34]. However, small fragments can also remain mobile where size permits transport through pore spaces. García-Haba et al. [17] reported MPs smaller than 100 µm were frequently detected in the effluent, despite high overall retention. This suggests particle shape either enhances retention or promotes mobility depending on particle size, pore geometry, and flow conditions.

Surface properties and water chemistry are also relevant, particularly for smaller particles that are not retained by simple straining. Surface charge, hydrophobicity, roughness, and weathering may influence attachment to aggregates, sediments, or biofilm-coated surfaces [34]. These mechanisms may become more important as PPS age and accumulate sediments and organic matter within the pore network. Direct evidence, however, on physicochemical attachment mechanisms in PPS remains limited, and current understanding is inferred from broader porous media studies [34].

Another important factor is the hydraulic loading conditions. Higher rainfall intensity or increased flow velocity can reduce retention by increasing mobilisation and reducing contact time between particles and retention surfaces. Kong et al. [48] observed reduced MP retention as rainfall intensity increased, suggesting that storm intensity may influence breakthrough. The influence of other key hydraulic variables, such as extreme rainfall intensity, rainfall duration, repeated wetting and drying, antecedent moisture and temporal rainfall pattern on MP retention or breakthrough in PPS remains unexplored.

3.4.2. Transport and retention mechanisms in PPS

As microplastic-laden rainfall or runoff enters the system, particles first encounter the surface layer or joint openings, before moving into the bedding, geotextile, sub-base, or drainage outlet [17,23,34]. This may vary in PC/PA and PICP as illustrated in Fig. 9. Particles, particularly larger ones, are generally strained, filtered, or entangled at or near the surface. Smaller particles that enter pore spaces may be further influenced by attachment to mineral surfaces, retained sediments, organic matter, or biofilms [34].

In newly constructed or relatively clean PPS, pore geometry and hydraulic loading may strongly control particle movement. Particles larger than the available pore throats or joint voids are more likely to be retained near the surface or upper filtration layers. Smaller particles may

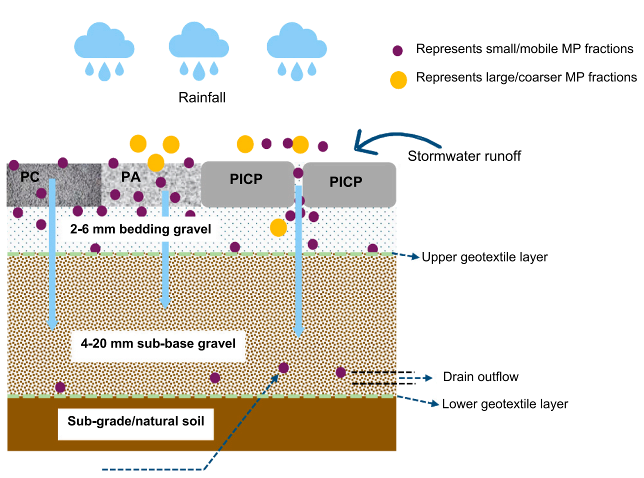

Fig. 9. Conceptual representation of MP transport and retention pathways in PC, PA and PICP. Particle retention and breakthrough are controlled by the interaction between particle-size/pore-throat ratio, density, shape, surface properties, pavement pore structure, joint configuration and hydraulic loading. Coarser particles may be retained near the surface, joints, bedding or geotextile layers by straining, interception or sedimentation, while finer or more mobile fractions may migrate through connected pores or layer interfaces and appear in the effluent. The direction and depth of transport are conceptual and should not be interpreted as controlled solely by particle size or density.alone.

penetrate more deeply, particularly under higher rainfall intensity or where connected pore pathways are present [17,48]. However, behaviour can also depend on the interaction effects of particle size, density, shape, and surface properties. For instance, PET, characterised by a larger MP size (112 µm), was more likely to penetrate the layers than PE, a smaller MP (40 µm) that tends to be retained on the surface [41]. This observation suggests that the type and density of the polymer can interact with the pavement's pore structure and rainfall intensity to affect transport dynamics.

Additionally, as PPS accumulate sediment and particulate matter, retention mechanisms may change. Accumulated materials can reduce pore spaces, increase filtration, and provide additional surfaces for particle attachment [17,61]. However, clogging may also reduce hydraulic capacity, promote surface runoff, generate preferential flow, or increase the risk of remobilisation during intense rainfall or maintenance [61–63]. This means that clogging may improve retention of some particles while creating new pathways for bypass or release. Current PPS-MP studies have focused mainly on short-term retention, while remobilisation and long-term redistribution within the pavement profile remain less understood.

3.4.2.1. Transport and retention mechanisms in permeable concrete (PC) and porous asphalt (PA).

Permeable concrete and porous asphalt are characterised by continuous interconnected voids [23,64]. In PC, the voids are formed by open-graded aggregates bound by cementitious paste, while in PA they are formed by open-graded aggregates bound with bitumen [23,57]. Because infiltration occurs across much of the surface, MPs can enter through multiple pore openings and move through a distributed internal void network. Retention may occur at the surface, within near-surface pores, along internal pore walls, or at zones where pore throats narrow [34,49].

The smaller and more tortuous pores of PC and PA may increase opportunities for interception and straining. This may explain the high overall retention in PC reported in Kong et al. [48] and García-Haba et al. [17]. However, fine-particle breakthrough can still occur where small particles pass through connected pores or preferential pathways. García-Haba et al. [17] observed high retention in PC but also reported that fine fragments below 100 µm were common in the effluent. This indicates that PC can retain a substantial overall particle load while the escaping fractions remain dominated by smaller, more mobile fragments.

This distinction is important when comparing PC with PICP. PC may provide greater pore-scale filtration due to its smaller pore structure compared with the wider joints in PICP [26,60]. At the same time, the continuous pore network of PC may allow some fine particles to move through connected voids, particularly under hydraulic loading. García-Haba et al. [17] reported that the proportion of small fragments in PC effluent was approximately 80–90%, compared with 40–60% in PICP effluent. This does not necessarily imply that PC has lower overall retention; rather, it indicates that the particles escaping from PC may be more strongly dominated by fine fragments.

PC and PA are also susceptible to clogging due to accumulation of fine sediments and organic matter within their pore networks [61]. Early clogging may reduce effective pore size and enhance filtration, but progressive clogging can reduce hydraulic conductivity and alter flow pathways. In long-term operation, this may lead to surface ponding, bypass flow, or potential remobilisation of retained microplastic particles during high-intensity rainfall or maintenance activities [61,62]. Therefore, it is crucial to evaluate the retention performance of PC or PA, as well as the development of clogging. Additionally, PA may accumulate road-derived particles due to its direct exposure to traffic, tyre abrasion, and pavement wear. Rasmussen et al. [32] showed that PA road and parking lot dust contained substantial quantities of TWPs and other MPs. This indicates that PA may act as a retention medium or a temporary surface on which road-derived particles accumulate before being mobilised or removed during maintenance.

3.4.2.2. Transport and retention mechanisms in permeable interlocking concrete pavement (PICP). As infiltration in PICP occurs mainly through the joints between impermeable blocks [23], particle transport is more strongly controlled by the joint-bedding interface than in PC or PA, where infiltration is distributed through a continuous surface pore network (Fig. 9). This gives PICP a distinctly layer-based transport pathway in which particles first enter through aggregate-filled joints before moving into the underlying layers.

The primary retention zones in PICP are the surface joints, bedding layer, and geotextile interfaces [17,60]. Jointing material, commonly composed of 2–6 mm aggregates [23,65], acts as the first filtration zone where particles may be retained by straining, interception, sedimentation, or surface attachment [17,23,65]. Particles that pass through the joints may then be retained in the bedding layer or at the upper geotextile, where changes in pore size, aggregate texture and flow direction can promote further interception [17].

Because the paving blocks are impermeable and water enters mainly through the joints, particle loading is not uniformly distributed across the bedding layer. Instead, sediment and particle accumulation tend to concentrate in the bedding aggregate directly beneath the joints, while other portions of the bedding layer remain less exposed. This behaviour was demonstrated by Lucke [66], who reported that much of the clogging in PICP occurs in the bedding aggregate immediately below the paving joints, leaving other areas of the bedding layer relatively underused. This concentrated joint-controlled pathway may partly explain why fine fragments were proportionally more common in PC effluent than in PICP effluent, as reported by García-Haba et al. [17], even where both systems showed high overall retention. In PC, particle loading is more evenly distributed across the surface pore network, whereas in PICP, particles are more likely to encounter jointing aggregate, and some portions of the upper bedding layer and geotextile interfaces before reaching the outlet.

To address the localised nature of flow and clogging in PICP, Lucke [66] tested lateral drainage slots cut into the underside of permeable paving blocks to allow sediment-laden water to spread laterally and access a greater surface area of bedding aggregate. The drainage-slot designs deposited substantially more sediment beneath the pavers than the control pavement, indicating that block geometry can influence how particles are distributed and retained within the bedding layer. For MP transport, this suggests that design modifications that improve lateral flow distribution may increase contact between MP-laden stormwater and the bedding aggregate, potentially enhancing particle interception and delaying localised clogging. However, this potential has yet to be tested for MPs or TWPs, and further research is needed to understand its influence on MP transport and retention in PICP.

Additionally, moderate accumulation of sediment and MPs in the joints can reduce pore spaces and may increase filtration of finer particles over time [17]. However, excessive joint clogging can reduce infiltration capacity, increase surface runoff and create the potential for bypass flow or remobilisation during intense rainfall. Maintenance activities such as vacuuming or pressure washing can target surface and joint zones, but retained particles must be properly managed to avoid secondary release [62,63].

3.5. Retention efficiency of MPs by PPS

The reviewed studies generally report high short-term MP retention by PPS under tested conditions. However, the reviewed studies differ substantially in experimental scale, pavement configuration, microplastic size, shape, polymer type, influent matrix, rainfall or hydraulic loading, analytical method, and reporting unit (see Table 4). Several studies reported retention efficiency above 90%, but experimental scales varied significantly. Kong et al. [48] reported more than 90% retention of synthetic PE and PET particles in permeable pavement blocks under controlled laboratory and modelling conditions. Their results showed that retention was influenced by pavement pore structure, permeability, polymer type and rainfall intensity. Low-density PE was retained more effectively than higher-density PET, and retention efficiency decreased as rainfall intensity increased [48].

Similarly, García-Haba et al. [17] reported high overall retention in PICP and PC systems, with values ranging from 89.0% to 99.6% depending on pavement type and particle characteristics. The upper surface and geotextile layers were identified as key retention zones, suggesting that retention performance should be interpreted alongside the vertical distribution of retained particles and the characteristics of particles that escape the system.

Mitchell and Jayakaran [19] reported more than 96% retention of synthetic TWPs in PC and PA configurations, including systems with and without cured carbon fibres. This finding supports the potential of permeable pavements to retain tyre-related particles under controlled field conditions. However, the study used a known TWP surrogate dose and reported retention under specific test conditions, which may make it difficult to compare performance under real conditions. In contrast, Rasmussen et al. [32] reported 105.02 mg/m^2 retained areal load for TWPs and 4.52 mg/m^2 for other MPs from PA road and parking lot dust. This outcome provides useful evidence on particle accumulation in real pavement settings, but it is not directly comparable with reported laboratory retention capacity of PPS.

The evidence therefore supports the conclusion that PPS can provide short-term MP retention under specific experimental, field or in-situ monitoring conditions. Furthermore, differences in influent type are particularly important. The reviewed studies have used a variety of sample matrices including direct rainfall, synthetic stormwater, road dust, sediment, known particle dosing, infiltrated water and outlet effluent [17,19,20,32,48]. These matrices differ in particle concentration, organic matter, sediment content, and polymer diversity, all of which can affect both retention behaviour and detection reliability. Additionally, analytical techniques may also influence reported efficiency. Some studies used polymer-confirmation techniques such as μFTIR, Raman spectroscopy, or combined μFTIR and Py-GC/MS, while others relied on visual identification, mass-based quantification, or chemical markers (see Table 4).

3.5.1. Innovative strategies for enhancing MPs retention in PPS

Recent studies have investigated material amendments and design modifications to enhance microplastic (MP) retention in PPS. These strategies focus on improving particle interception by modifying jointing materials, increasing pore tortuosity, strengthening filtration zones, or enhancing the mechanical and hydraulic performance of pavement materials. Current evidence, however, is limited, and most approaches have not been validated for long-term MP mitigation under realistic field conditions.

García-Haba et al. [17] investigated the use of drinking water treatment sludge (DWTS) as a partial replacement for conventional jointing material in PICP. DWTS is a waste by-product from drinking water treatment plants and has previously been reported to reduce phosphorus concentrations in effluent when applied as a jointing material in interlocking permeable pavement [68]. In the context of MP retention, García-Haba et al. [17] replaced 20% of conventional joint filler with DWTS in PICP to assess retention capacity. However, the study found no significant improvement in MP retention, likely due to the insufficient quantity applied to achieve a measurable effect. While DWTS may provide circular-economy advantages by repurposing waste-derived material, its economic efficiency for MP mitigation in PPS has been insufficiently evaluated. Future research should assess not only retention performance, but also material availability, processing requirements, transportation costs, installation feasibility, hydraulic conductivity, clogging potential, maintenance requirements, and life-cycle costs before DWTS can be recommended as a practical amendment for

MP control.

Mitchell and Jayakaran [19] examined the incorporation of cured carbon fibres into PC and PA configurations to enhance both mechanical performance and TWP retention. Their study reported more than 96% retention of TWPs, suggesting that fibre incorporation may improve particle interception and address some mechanical limitations associated with highly porous pavement materials. Nevertheless, the long-term performance of fibre-amended PC and PA remains uncertain. Further work is required to determine how such amendments affect hydraulic conductivity, clogging susceptibility, structural durability, maintenance requirements and performance under repeated rainfall and traffic-related loading.

Other studies have explored tyre-derived or recycled plastic materials for PPS applications, primarily to improve sustainability, hydraulic performance, or mechanical behaviour, and to mitigate plastic pollution. De la Colina Martínez et al. [69] investigated the use of recycled e-polycarbonate from electronic waste as a partial aggregate replacement in PC and reported that higher e-polycarbonate content, particularly a 9% replacement by volume, improved selected mechanical and hydraulic properties. Ryu et al. [70] developed PC blocks using recycled PET aggregate and reported promising performance, including high permeability, adequate flexural strength, resistance to clogging, and freeze-thaw durability. Similarly, Raeesi et al. [71,72] investigated waste tyre permeable pavements containing tyre-derived aggregate and polyurethane binder, showing that these systems can provide hydrological and water-quality benefits while offering a reuse pathway for waste tyres. These studies demonstrate the potential of recycled plastic and tyre-derived materials in permeable pavement design. However, the unintended shedding or release of MPs from these technologies into the environment requires further research. Evidence from plastic-modified impermeable pavements indicates that recycled plastic-modified pavements can release MPs under laboratory abrasion, moisture, or traffic-simulation conditions [73–76]. These studies provide significant evidence that plastic- or tyre-derived construction materials must be assessed not only for mechanical and hydraulic benefits but also for long-term risks of abrasion, weathering, hydraulic scouring, and particle release. Long-term field evidence also suggests that permeable pavement may act as pollutant sinks. Calzadilla-Cabrera et al. [67] reported substantial MP accumulation in five-year-operational in-situ PC slabs under real urban conditions, compared with new manufacturer-supplied PC slabs. This evidence supports the conclusion that the upper surface of PPS layers can retain MPs over extended periods. However, it also raises important questions about the long-term fate of these retained particles, including whether they remain immobilised, undergo further fragmentation, or become remobilised during maintenance or intense rainfall events. These findings underscore the necessity of evaluating amended PPS materials under realistic service-life conditions rather than relying solely on short-term retention or material-performance indicators.

Furthermore, biochar has been proposed as a sorptive material to address MP pollution. Asoharasa et al. [77] noted that previous studies have demonstrated the feasibility of using biochar to treat MP and highlighted the need to further exploit its adsorption potential to retain MP in PPS. However, biochar has yet to be implemented and validated as an amendment to enhance MP retention in PPS. Future research could investigate whether biochar-amended bedding, jointing materials, or filter layers can improve the retention of fine MPs without causing unacceptable reductions in infiltration capacity, hydraulic performance, or maintenance efficiency.

Overall, these strategies show promise but remain in their early stages of development. A holistic approach must consider hydraulic performance, structural strength, clogging behaviour, maintenance requirements, durability under environmental exposure, potential secondary MP release, economic feasibility, and life-cycle impacts. This is crucial, as materials introduced to improve retention or sustainability may alter flow pathways, increase the risk of clogging, or create new environmental trade-offs if their long-term behaviour is not well understood.

4. Conclusions and future outlook

This review synthesised current evidence on the transport, retention, detection, and removal of MPs in PPS. Twenty-eight peer-reviewed English-language studies published between January 2000, and May 2026 were identified through Scopus, Web of Science, and Google Scholar. The findings indicate that research on MP mitigation by PPS remains in its early stages, with most studies published in the last five to six years and largely based on laboratory experiments or short-term monitoring. Although reported studies show promising short-term retention under tested conditions, retention of MPs within pavement layers or reductions in effluent concentrations should not be interpreted as permanent removal or long-term mitigation without consideration of particle fate, remobilisation, and maintenance-related release.

The available evidence demonstrates that PPS can effectively intercept MPs and tyre-related particles within surface, jointing, bedding, geotextile, and underlying porous layers. However, reported performance varies considerably with pavement configuration, hydraulic loading, influent characteristics, particle properties, and analytical methods. A key finding is that fine MPs, particularly small fragment-shaped particles (<100 μm), are frequently detected in effluent, indicating that high overall retention efficiencies may mask the continued breakthrough of finer particles. Microplastic transport in PPS is governed by complex interactions among particle size, pore-throat ratio, density, shape, surface properties, pavement pore structure, joint configuration, clogging conditions, and hydraulic loading. Consequently, permeable pavement design for MP mitigation should not be based solely on total retention/removal efficiency but should also consider the types of particles retained, their locations within the pavement profile, and the fractions that escape into the effluent.

The review further highlights substantial methodological inconsistencies in sampling, extraction, quality assurance, polymer identification, and reporting, which limit cross-study comparability and confidence in reported performance. These differences further influence whether studies detected visually suspected particles, polymer-confirmed MPs, TWPs, retained loads, or effluent breakthrough. Harmonised protocols are therefore essential to improve cross-study comparison and strengthen confidence in reported performance. Emerging material and design innovations, including drinking water treatment sludge-amended joint materials in PICP, cured carbon fibres in PC and PA, recycled e-polycarbonate aggregates in PC, and plastic- or tyre-derived additives in permeable pavements, show potential for enhancing retention and hydraulic performance, but their long-term effectiveness remain uncertain. Future evaluation should consider not only short-term retention, but also hydraulic conductivity, clogging susceptibility, structural durability, maintenance requirements, economic feasibility, life-cycle impacts and potential secondary MP release, particularly where plastic or tyre-derived amendments are used.

Overall, PPS show considerable promise as source-control measures for reducing MP loads. However, current evidence should be interpreted as support for short-term interception rather than long-term environmental risk reduction. Future research should prioritise long-term field monitoring, mass-balance assessments, layer-specific particle recovery, remobilisation studies under repeated or extreme rainfall events, maintenance-related releases, improved TWP detection, and optimisation of pavement designs for fine-particle retention (see Table 5). Addressing these priorities is critical to determining PPS's capacity to deliver reliable and sustainable MP risk reduction under real-world conditions.

Environmental implication statement

Microplastics in urban stormwater are environmentally hazardous due to their persistence, mobility, and transport to receiving waters and

Table 5
Critical knowledge gaps and future research priorities for MP mitigation through permeable pavement systems.

Critical knowledge gap	Why this matters for MP hazard/risk evaluation	Priority research direction
Long-term fate, accumulation and remobilisation of retained MPs	Most studies assess short-term retention under controlled or limited monitoring conditions. Retained MPs may accumulate, fragment, age, or be remobilised during subsequent rainfall events, maintenance activities, or hydraulic disturbance.	Conduct long-duration laboratory and field studies to quantify accumulation, aging, fragmentation, remobilisation and maintenance-related release under realistic service-life conditions.
Fine-particle breakthrough and vertical transport through pavement layers	Small fragments below 100 μm are frequently reported in effluent, while the extent of downward migration through bedding, geotextile, sub-base and underdrain pathways remains uncertain.	Undertake layer-by-layer sampling and effluent monitoring to quantify size-dependent retention, vertical distribution and breakthrough of fine MPs and nanoplastics.
Limited evidence on TWPs and road-derived particles	TWPs are highly relevant to road runoff, but their identification and quantification remain difficult, and PPS-specific evidence remains limited.	Prioritise studies on tyre wear and tyre-road wear particles using appropriate chemical markers, polymer confirmation methods, and realistic road dust/stormwater matrices.
Lack of harmonised sampling, detection and reporting protocols	Cross-study comparison is limited by differences in sample matrices, extraction methods, detection limits, QA/QC, polymer confirmation and reporting units.	Develop minimum reporting standards for PPS-MP studies, including sample matrix, extraction method, QA/QC, detection limit, recovery tests, polymer confirmation and retention/removal metrics.
Influence of rainfall intensity, clogging and repeated hydraulic loading	Extreme or repeated rainfall may mobilise retained particles, while clogging may either enhance filtration or promote bypass, runoff, and remobilisation.	Examine how rainfall intensity, duration, temporal pattern, antecedent conditions, clogging, and maintenance affect retention, breakthrough, and washout.
Long-term performance of amended or modified PPS materials, including biochar-based amendments	Amendments such as DWTS, cured carbon fibres, recycled e-polycarbonate, tyre- or plastic-derived materials, and potential sorptive materials such as biochar may improve retention, but their durability, cost, hydraulic performance, and secondary-release risks remain uncertain.	Evaluate amended PPS materials, including biochar-amended bedding and jointing or filter layers, for retention efficiency, hydraulic conductivity, clogging risk, structural durability, maintenance requirements, economic feasibility, life-cycle impacts, and possible secondary MP release.

groundwater. This review demonstrates that permeable pavement systems (PPS) can serve as important source-control measures by intercepting a significant proportion of microplastics before environmental release. However, smaller particles, particularly fragments below 100 μm, remain difficult to retain and are often detected in effluents. While PPS may reduce pollutant exposure, long-term and reliable hazard mitigation requires harmonised monitoring, field validation, and better understanding of their fate, remobilisation, and secondary release pathways.

CRediT authorship contribution statement

Bockarie Samai: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Abiy S. Kebede:** Writing – review & editing, Writing – original draft, Validation, Supervision, Conceptualization. **Carola König:** Writing – review & editing, Writing – original draft, Supervision. **Pedro Martin-Moreta:** Writing – review & editing, Writing – original draft. **Alalea Kia:** Writing – review & editing, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2026.143096.

Data availability

All data were retrieved from published literature and are available upon request from the corresponding authors.

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