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Review

Microplastics in the riverine environment: Meta-analysis and quality criteria for developing robust field sampling procedures

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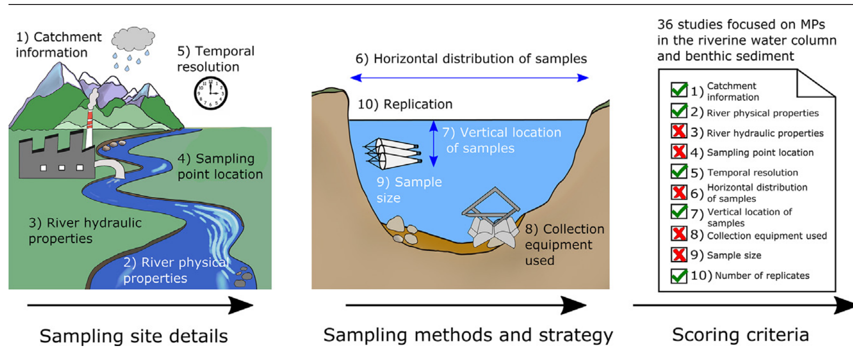
HIGHLIGHTS

- Criteria were developed to score the quality of 36 river MP sampling studies.
- MP water column and riverbed sampling approaches were assessed using the criteria.
- 35 out of 36 studies received a score of 0 for at least one quality criterion.
- Documentation of river physical and hydraulic characteristics scored the lowest.
- MP concentration in river water and sediment varied by 5 and 7 orders of magnitude.

GRAPHICAL ABSTRACT



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ABSTRACT

Current sampling approaches for quantifying microplastics (MP) in the riverine water column and riverbed are unstandardised and fail to document key river properties that impact on the hydrodynamic and transport processes of MP particles, hindering our understanding of MP behaviour in riverine systems. Using ten criteria based on the reportage of the catchment area, river characteristics of sampling sites and approach, we reviewed the sampling procedures employed in 36 field-based river studies that quantify MP presence in the water column and benthic sediment. Our results showed that a limited number of studies conducted reliable sampling procedures in accordance with the proposed quality criteria, with 35 of the 36 studies receiving a score of zero for at least one criterion, indicating the omission of critical information relating to the study's sample size and the physical and hydraulic characteristics of the sampled river. On the other hand, a good number of studies adequately documented the spatial information of the sampling sites, the vertical location of sample collection, and sampling equipment used. An idealised MP sampling approach is presented to ensure that future studies are harmonised and variables underpinning MP transport in rivers are reported. In addition, a meta-analysis on MP particle characteristics from these studies found that concentrations in the riverine water column and benthic sediment are highly variable, varying by five and seven orders of magnitude respectively, and are heavily dependent on the sampling equipment used. Polypropylene (PP), polyethene, (PE), polystyrene (PS), polyethylene terephthalate (PET) and polyvinyl chloride (PVC) were the most frequently reported MP polymers, while irregular-shaped particles, fibres, spheres, and films were the most commonly reported shapes in the river studies. These results highlight the urgent need to standardise sampling procedures and include key contextual information to improve our understanding of MP behaviour and transport in the freshwater environment.

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Contents

1. Introduction

Microplastic (MP) pollution, defined as plastic particles smaller than 5000 μm in size, has caused global alarm over its widespread distribution, high concentration and possible environmental impact in the aquatic environment (Galloway et al., 2017; Li et al., 2018; Skalska et al., 2020). The ingestion of MPs has been reported for organisms at almost all trophic levels (Cole et al., 2013; Jâms et al., 2020). The impact of MP exposure to freshwater biota is still largely debated, however, results from laboratory exposure experiments have suggested that ingestion by benthic invertebrates can evoke toxic and physical effects (Haegerbaeumer et al., 2019). MPs can also potentially serve as vectors, enhancing the transport of pathogens, organic contaminants and invasive species attached onto the MP particle's surface, as well as leaching toxic compounds into the surrounding ecosystem (Bakir et al., 2014; Hermabessiere et al., 2017). Once MPs are ingested, the harmful impacts of these substances may bio-magnify from lower trophic organisms to top predators, impacting the whole food chain (D'Souza et al., 2020).

Riverine ecosystems are generally understudied for the presence of MPs, despite contributing as much as 80 % of the overall load of plastic pollution to the world's oceans (Meijer et al., 2021). MPs are sourced from the fragmentation of large plastic waste, the breakdown of textiles, or from purposely manufactured small plastic particles, and can enter the riverine systems through direct disposal (e.g. littering, combined sewage overflows, wastewater treatment plant outflows), airborne dispersal and run-off (Allen et al., 2019; Woodward et al., 2021; Lofty et al., 2022). The varying size, density and shape of MP particles found in the environment impacts on their buoyancy, settling velocity, and critical bed shear stress, making it challenging to predict their transport and distribution (Waldschläger and Schüttrumpf, 2019b; Khatmullina and Chubarenko, 2020; Waldschläger et al., 2022). In addition, rivers are shallow flow systems, and their meandering and morphological features lead to complex hydrodynamic processes that can significantly impact MP transport and distribution (Corcoran et al., 2020; Haberstroh et al., 2021). Temporal and spatial variations in the local velocity between sampling point locations, as well as sampling point location with respect to bed features can have a major impact on the MP concentration distribution in both the water column and riverbed, raising uncertainty of the study's results if not reported (Mani et al., 2015; Tibbetts et al., 2018). MP concentrations in the water column and benthic sediment may also fluctuate in response to recent rainfall events or seasonal wet and dry cycles (Nel et al., 2018; Campanale et al., 2020; Skalska et al., 2020). High discharge events following rainfall lead to elevated bed shear stresses resulting in the remobilisation of legacy MPs from the riverbed sediment into the main flow, thus increasing MP concentration in the water column (Hurley et al., 2018). The grain size and grading of the bed layer may also affect the remobilisation threshold for MPs; a bed with a grain size larger than a MP particle can shelter MP particle from the flow, requiring a higher bed shear stress for initiation of motion, compared to a smaller grain size bed, where MPs are more exposed and can be remobilised at lower shear stresses (Fenton et al., 1977; Waldschläger and Schüttrumpf, 2019b).

Further research is urgently required to understand the transport dynamics of MP particles in a riverine setting, as well as the interaction of MPs with the benthic layer and riparian zone to assess the potential risk posed to organisms. However, MP research in rivers must be carried out with a hydraulic and geomorphic awareness, using sampling procedures that are accurate, representative and providing details that allow the study to be compared to prior and future studies. Currently, sampling procedures for surface floating MPs, suspended MPs and riverbed MPs are not standardised and results between studies are not comparable (Cowger et al., 2020; Skalska et al., 2020). The rapid rise in published MP studies has resulted in the use of sampling methods from a variety of disciplines, e.g. earth sciences, geotechnics and river engineering, which are appropriate for specific particle sizes, shapes or density and are likely being used outside of their range of suitability, leading to unrepresentative, bias or incomparable results (Karlsson et al., 2020; Watkins et al., 2021). The lack of a standardised MP sampling methodology brings uncertainty into assessing MP concentration and distribution in rivers, and thus the severity of the associated ecological risks of MP pollution could be erroneous if poor quality methodology is exercised (Brander et al., 2020; Provencher et al., 2020; de Ruijter et al., 2020).

In ecotoxicological monitoring for other aquatic contaminants, such as heavy metals, persistent organic pollutants and phosphorus, standardised and quality controlled sampling methodologies are common, driven by Water Quality Directives (European Commission, 2000; Water Framework Directive, 2017) and environmental regulating bodies (e.g. UNEP, Environmental Agency). Conversely, standardised MP sampling methods for beach sand (Besley et al., 2017), marine sediments (Frias et al., 2018) and seawater (Gago et al., 2018) have been proposed. The only related recommendation for the documentation of MP sampling protocols are minimum reporting standards in order for MP research to be reproducible, comparable and interpreted easily for the wider scientific community (Dehaut et al., 2019; Cowger et al., 2020). In the development of sampling procedures which are reliable, comparable and unbiased, the first step should be to evaluate the current quality of related published MP studies. While previous reviews have evaluated the quality of laboratory procedures and ecotoxicity data for MPs in freshwater, seawater, drinking water, bottled water and biota (Koelmans et al., 2019; de Ruijter et al., 2020; Praveena and Laohaprapanon, 2021), they focus primarily on the laboratory analyses rather than how the MP water and riverbed samples are taken in the field. Inadequate field sampling procedures will inevitability lead to poor quality data regardless of the quality in subsequent laboratory analyses (Zhang et al., 2014). Therefore, the development of a quality assessment criteria for sampling MPs in riverine water column and benthic sediment is of upmost importance and lead towards the standardisation of sampling approaches for a river setting.

This paper aims to present a quality criteria method designed to ensure that variables underpinning MP transport in rivers are reported together with data quality metrics of the field sampling process in terms of precision, representability, comparability, and completeness. We review and score the sampling procedures of 36 river-based studies, that were specifically chosen based on the range of MP sampling methods deployed to collect MP particles in the water column and riverbed, using a quality criteria method to understand the current position of MP research in the river environment. A scoring method was used to highlight studies conducting the most appropriate sampling procedures and identify areas which need improving for MP river research. An idealised MP sampling approach is presented, with the goal of establishing a standardised framework for high-quality sampling and ensuring that the quality criteria are met. In addition, a meta-analysis of riverine MP data reported in these studies was undertaken to assess the variation in MP abundance and the range of MP physical properties observed in the sampled rivers.

2. Methods

2.1. Overview of the MP sampling quality criteria

This paper proposes a sampling quality framework based on ten criteria, which are described in Table 1 and justified in (Section 2.4). The quality criteria can be used to improve MP sampling procedures in the water column and benthic sediment and which can be employed by researchers and stakeholders to evaluate the quality of collected field samples. The criteria are based on to data quality objectives for collecting high-quality field data which examines sampling in terms of: 1) accuracy, 2) representativeness, 3) comparability and 4) completeness (Zhang et al., 2014). These four objectives aim to minimise the uncertainty from the methodology used to collect MPs from the water column and benthic sediment, as well as ensuring that details of the sampling procedure and study context are documented.

The ten criteria are split into two subsets: *Sampling site details* and *Sampling methods and strategy*. The first subset of criteria, *Sampling site details* (criteria 1–5), allows for an assessment of the general characteristics of sampling site, and study context which can be used to explain MP variability (Section 2.4.1). The second subset of criteria, *Sampling methods and strategy* (criteria 6–10) relates to the suitability of the MP sampling strategy used to obtain MPs from the riverine environment and reportage of the sampling equipment deployed (Section 2.4.2).

Selected studies were scored against each of the ten criteria from the proposed sampling quality framework, with a score of zero, one or two depending on their adherence to the quality criteria indicated. A score of two suggests that a high level of detail was reported and the sampling procedure met all the objectives required for collecting quality field samples. A score of one indicated that less details were provided, and the objectives needed for collecting high-quality field samples were partially met. A score of zero was assigned when no details related to the criterion were reported and/or the sampling procedure did not meet the data quality objectives in terms of accuracy, representativeness, comparability and completeness. To account for the study's data quality standard, a total score was calculated by summing up the scores for each criterion, with a maximum possible score of 20 points. An average score per criterion was also calculated to compare them and identify components of MP riverine water column and benthic sediment sampling procedures that would benefit most from improvement. An average score per criterion of less than one indicates significant improvements are required, while an average score of 1.0–1.9 indicates that the criterion has been reported well, but there is still room for improvement, and an average score of >1.9 indicates that the criterion has been met for the majority studies.

2.2. Literature review

A total of 36 Scopus-indexed studies that reported MP particle concentrations in the riverine environment in the period 2015–2021 were identified using a keyword search that included: ("microplastic") AND ("river" OR "sediment" OR "riverbed"). The 36 papers comprise of four studies that investigated MP particle concentration in both the water column and benthic sediment, 20 studies that investigated the water column, and 12 studies that focused on the benthic sediment. To capture the current position in MP river field-based research and to avoid bias, these studies were selected based on the range of sampling equipment used (net, pump, bulk, grab, core or manual sampling), sampling strategy (point sampling or transect sampling), land usage (urbanised, agricultural or rural), catchment reach location (upper, middle or lower), and river characteristics (dimensions, riverbed or planform characteristics).

2.3. Meta-analysis of MPs in the riverine environment

From the selected studies, MP concentration data (minimum, maximum, range and mean), sample size, sample location, MP particle size distribution, lower/upper size limits for MP retention, and information relating to MP shape and polymer type were extracted for analysis. Units used for MP concentration data were converted where possible into two metrics: particle count per volume (MP count/m^3) for MPs found in the water column, and MP particle count per dry sediment weight (d.w) (MP count/kg) for MPs found in the benthic sediment. The meta-analysis omitted studies whose MP concentration units could not be converted to MP count/m^3 or MP count/kg. Similarly, those who did not report MP size, shape or polymer type were excluded from meta-analyses.

2.4. The MP sampling quality scoring criteria

2.4.1. Subset 1: sampling site details

2.4.1.1. Criterion 1: catchment information. In order to determine the scale of the study and its context, the catchment area, sampled river length, potential sources of MP input, and recent rainfall events should be reported. Several authors have noted the presence of point sources of pollution such as wastewater treatment plants, sewage pipes and industrial facilities in close proximity to the sampling site which have increased the abundance of MPs, e.g. in a small scale study in the North Shore Channel (USA), MP concentrations in the water column increased more than eight times downstream of a wastewater treatment plant outlet pipe compared to upstream concentrations (McCormick et al., 2014). Case study sites with different land use also have an impact on MP abundance in rivers, e.g. on the Dommel river (Netherlands) the highest concentration of MPs was observed on the surface water near two major cities (Mintenig et al., 2020),

Table 1

MP sampling quality criteria proposed to improve the reliability of data obtained from sampling the riverine water column and benthic sediment. Criteria aim to ensure that key information relating to the sampling sites and sampling approach is reported, which ensures that the data produced by the study are accurate, representative, comparable and reproducible. A score of 0, 1, 2 points were awarded depending on the studies adherence to the criteria stated.

No	Criteria	Score		
		0	1	2
Sampling site details				
1	Catchment information	Not reported	A subset of desired characteristics.	Catchment area, Sampled reach length, Land use, Recent rainfall events Potential diffuse sources, Potential point sources.
2	River physical properties	Not reported	A subset of desired characteristics.	Mean width, Mean depth, Longitudinal bed slope, For benthic sediment studies, information relating to the riverbed type (sand, gravel) or some bed grain size information (d_{50}, σ_g). Characteristics given directly or able to be calculated
3	River hydraulic properties	Not reported	A subset of desired characteristics or characteristics reported but with no record over time or space.	Discharge, Velocity, Flow depth (stage). Information included at each sampling point and over the sampling period (If the study conducted a temporal sampling campaign).
4	Sampling point location	Not reported	A subset of desired characteristics.	Geographical coordinates (GPS) or inclusion of a map of an equivalent spatial resolution. Compromises may be made where the aim of the study does not require spatial variability e.g. temporal sampling at only one location.
5	Temporal resolution	1 point in time	One point in time with justification included e.g. pertinent flow condition, accessibility, citizen science approach.	Sampling date(s), Sampling taken on two or more dates for a given sampling point.
Sampling methods and strategy				
6	Horizontal distribution of samples	Insufficient description of the horizontal sampling points. E.g., 'samples taken from the river'.	A limited description of the horizontal sampling points. E.g., 'samples taken from the in-channel and banks'. Compromises may be made where accessibility to the river is limited but must be stated.	A detailed description, with specific measurements, of the horizontal sampling points. E.g., 'samples were taken 0.5 m away from the riverbank'.
7	Vertical location of samples	Insufficient description of the elevation of sampling points. E.g. 'river water was taken'. E.g. 'river sediment was taken'.	A limited description of the elevation of sampling points within the water. E.g. 'samples taken from surface waters'. E.g. 'samples taken from top layer of riverine benthic sediment'.	A detailed description, with specific measurements, of the elevation of sampling points. E.g. 'samples taken from the top 0–0.5 m of surface waters'. E.g. 'samples taken from the top 0–0.05 m of riverine benthic sediment'.
8	Collection equipment used	Insufficient description of equipment and deployment methods that does not allow study to be reproduced.	A subset of desired characteristics with limited reproducibility or use of unsuitable sampling equipment and deployment methods: Filter/mesh/sieve sizes used >330 μm.	A full description of suitable equipment used and deployment method so the study can be reproduced. Water column studies: Equipment type (e.g. Manta net, Teflon pump, Bottle, etc.), Filter/mesh sizes used (pump and net sampling) (<330 μm), Equipment dimensions (e.g. net opening area, grab area), Deployment time/length (net sampling). If applicable, nets deployed by the side of boats at a 2–4 m distance away from the boat. Benthic sediment studies: Equipment type (e.g. Van Veen grab, Ponar grab, etc.), Equipment dimensions (e.g. grab area, scoop size), Mesh sizes used (sieve sampling). If applicable, use of flow block to reduce the loss of fine sediment and microplastics during the collection process (manual sampling) (Fripp and Diplas, 1993).
9	Sample size	Water column studies: Not reported or <500 L sampled per site.	Water column studies: <500 L with good reason e.g. clogging up of nets due to high organic matter and must be stated in text.	Water column studies: A minimum of 500 L collected/filtered for analysis of microplastics per sampling point (Koelmans et al., 2019).

Table 1 (*continued*)

No	Criteria	Score		
		0	1	2
10	Number of replicates	Benthic sediment studies: Not reported or <400 g sampled per site. Not reported or no replicates taken.	Benthic sediment studies: <400 g with a good reason e.g. inaccessible riverbed, grab not being able to close properly due to coarse grain sediment and must be stated in text. 1 replicate sample per sampling point or sampling date.	Benthic sediment studies: A minimum of 400 g of benthic sediment collected/filtered for analysis of microplastics per sampling point (Masura et al., 2015). More than two replicate samples per sampling point or sampling date. Uncertainty analysis was undertaken.

D_{50} is the median sediment particle size. σ_g is the geometric standard deviation of the grain size.

while on the Snake and Lower Columbia rivers (USA) the highest MP concentration was found at a site located near agricultural land, potentially due to sewage sludge fertiliser run-off (Kapp and Yeatman, 2018). The magnitude of MP run-off from urban and rural landscapes will be influenced by rainfall events, with a number of studies observing significant increases in water column MP concentrations following rainfall events, e.g. MP abundance increased 40-fold (400 to 17,383 MP items/m^3) during two days of heavy rain in Cooks River estuary (Australia) (Hitchcock, 2020).

2.4.1.2. Criterion 2: river physical properties. To provide a perspective of the both the magnitude of the river in relation to its catchment area and flow system scale, the river's physical properties should be reported, e.g. mean bankfull width, depth and longitudinal bed slope. These properties may give some explanation to the variability of the MPs observed in the study's findings, e.g. on the Rhine river (Germany) a decrease in MP concentration in the water column was observed in those river sections with the lowest bed slope (and thus lower flow velocities). The bed grain size and bedform structure will also influence the hydrodynamics and bed shear stress distribution, determining whether MP particles are retained on the benthic substrate, transported as bedload, or as suspended load (Waldschläger and Schüttrumpf, 2019b). MP particle distribution may also follow deposition patterns similar to naturally occurring fine sediment particles with a few studies demonstrating a correlation between the abundance of specific grain fraction and MP concentration in the bed sediment (Enders et al., 2019; Hoellein et al., 2019). Furthermore the linkage between fine sediment grain size and MP accumulation has also been observed in studies on the Thames river (Canada) and the Tame river (UK) (Tibbetts et al., 2018; Corcoran et al., 2020).

2.4.1.3. Criterion 3: river hydraulic properties. The hydraulic characteristics of the river between sampling points and over the sampling period give an indication of the flow magnitude, hydraulic performance and variability of the hydraulic processes. Studies have demonstrated a link between areas of lower flow velocities, e.g. inner banks of river bends and areas with lower bed slopes, and higher MP abundance in the water column and benthic sediment, suggesting MPs accumulate and settle in these areas (Mani et al., 2015; Tibbetts et al., 2018; Corcoran et al., 2020). Discharge will remain constant through the river course if there are no inputs from tributaries or rainfall events, however, observations of this information need to be stated (criterion 1), especially for studies conducted over longer river reaches in which there are a high number of tributaries and/or land drainage inputs. Without the reportage of the spatial and temporal variability of the hydraulic characteristics of the river, the study's results do not provide the full context of the river's hydraulic processes linked to MPs presence and distribution (Skalska et al., 2020). Therefore, two points were awarded to studies that measured the hydraulic characteristics at each sampling point over the time window of the field campaign to capture the spatio-temporal variability of the flow hydraulics, while one point was awarded to studies that reported the hydraulic characteristics with no record over time or space, such as mean (bulk) velocity of the river reach. Studies that recorded no characteristics received zero points.

2.4.1.4. Criterion 4: sampling point location. MP concentrations in a river can differ significantly depending on the streamwise location of the sampling site on the river reach (Miller et al., 2017; Rodrigues et al., 2018; Crew et al., 2020). MP concentrations in the benthic sediment rose from 0 to 136,926 ± 83,947 MP items/m^2 between two sampling points located <10 km away from each other in the St. Lawrence river (Canada) (Castañeda et al., 2014). Therefore, the position of sampling sites along the river course and spatial resolution should be presented on a map, diagram or reported using geographical coordinates (GPS) in order to identify any spatial influence and possible sources of MPs along the reach (Cowger et al., 2020).

2.4.1.5. Criterion 5: temporal resolution. Studies have shown that MP concentrations in rivers are temporally variable, usually following seasonal rainfall patterns (Rodrigues et al., 2018; Eo et al., 2019; He et al., 2020; Mintenig et al., 2020). A number of studies have observed MPs concentrations in the water column to increase from the dry season to the wet season due to increased run-off, sewage discharge and remobilisation of MP from the sediment bed in high-flow conditions. For instance, Campanale et al. (2020) observed MP concentrations in the water column to increase from 0.9 to 13 MP items/m^3 during dry and wet seasons, respectively. The opposite pattern was observed for MP abundance in the benthic sediment, with concentrations increasing from the wet season to the dry season likely to be a result of lower flow velocities causing increased MP deposition onto the riverbed in the dry seasons (Nel et al., 2018; Wu et al., 2020). Without temporal resolution of MP concentration flux in rivers, a study can only provide a ‘snapshot’ of the MP concentration at the time of sampling.

2.4.2. Subset 2: sampling methods and strategy

2.4.2.1. Criterion 6: horizontal distribution of samples. MP concentrations vary horizontally across the river cross-section in both the water column and benthic sediment (Mani et al., 2015; Liedermann et al., 2018; Gallitelli et al., 2020). MPs tend to accumulate in the water column and settle into the riverbed in areas with low flow (Mani et al., 2015; Tibbetts et al., 2018; Corcoran et al., 2020). MP concentrations in rivers varied by an order of magnitude between the mid channel and the banks on the Tamsui river (Taiwan) and Rhine river (Germany) (Mani et al., 2015; Wong et al., 2020). Studies are required to report the specific sampling point relative to the river cross-section, e.g. true right- and left-hand bank looking in the downstream flow direction. Ambiguous terminology, such as ‘the middle of the river’ may add uncertainty to the sampling strategy and should be avoided (Cowger et al., 2020). Two points were awarded to studies that recorded specific measurements of the horizontal distribution of samples, e.g. ‘samples were taken 0.5 m away from the riverbank’, and one point was awarded to studies that only described the distribution, e.g. ‘samples were taken from the ‘mid river’ and ‘banks’’, but did not record specific locations. Studies that did not report any information on cross-sectional sampling position received zero points.

2.4.2.2. Criterion 7: vertical location of samples. It is understood that MP size, density, shape and settling velocity, as well as river hydrodynamics will dictate whether a MP particle is transported by bedload, suspended load or remains on the bed (Waldschläger and Schüttrumpf, 2019b; Khatmullina and

Chubarenko, 2020). However, the vertical distribution of MPs remains largely understudied despite being crucial in understanding the MP transport mechanisms in rivers. Sampling closer to the bed will have a major effect on the MP distribution measurement as this is where the highest concentration of riverbed particles in a mobile bed are present (Van Rijn, 1984). Significant variation in MP composition in terms of size, shape, and density has been found at different elevations in the water column, e.g. dense MP particles may reside near the bed of the river whereas more buoyant MPs will float near the surface waters (Lenaker et al., 2019).

Few studies have examined the variation of MP concentration with depth in the bed substrate layer. MPs have been discovered as deep as 0.5 m below the bed surface, with smaller MP particles and higher concentrations dominant in deeper layers of the riverbed (Niu et al., 2021). However, these correlations will be influenced by the sediment grain size and distribution in the active sediment layer of the riverbed in which particle exchange occurs between the sediment bed and water column (Frei et al., 2019; Skalska et al., 2020). Nevertheless, the majority of studies only take samples from the top layer (0–10 cm) of the bed layer, thus overlooking the variation of MP size, polymer and concentration at different vertical depths in the riverbed. Terminology such as 'surface waters', 'bottom waters' or 'the top layer of benthic sediment' may be interpreted differently and should be avoided, and the elevation at which samples were taken should be documented. Studies that reported on the specific elevation of sampling point, e.g. 'samples were taken from the top 0–0.5 m of surface waters', received two points, while studies that described the sampling elevation in broad terms, e.g. 'samples were taken from surface waters', received one point. No points were awarded to studies that failed to provide any information about the elevation at which samples were collected.

2.4.2.3. Criterion 8: collection equipment used. The sampling equipment and deployment procedures have a significant effect on the observed MP concentration and size in riverine samples (Cowger et al., 2020). In sampling the water column, the pore size of net's mesh or pore size of the filter used inside a pump will determine the lower size limit of MPs retained by the equipment (Covernton et al., 2019; Lindeque et al., 2020). The most widely used mesh/filter pore size for riverine water column sampling is 300–330 μm which is used in marine research to sample plankton (Arthur et al., 2009; Hidalgo-Ruz et al., 2012; Whitehead et al., 2021). Using a mesh/filer with pores sizes larger than 330 μm does not guarantee the capture of large amounts of small MPs, e.g. MPs <330 μm, and can result in misleading estimates of MP concentrations (Conkle et al., 2018; Covernton et al., 2019; Lindeque et al., 2020). The smallest size fractions of MPs are also of particular concern because they are thought to be the most abundant in rivers and ingestible to the widest amount of aquatic biota (Cole et al., 2013; Wright et al., 2013; Jâms et al., 2020). Therefore, two points were given to studies that used mesh/filter pore sizes <330 μm, while one point was given to studies that used mesh/filter pore sizes >330 μm.

The dimensions of the sampling equipment and how they are deployed will also affect the observed MP concentration and should be reported for transparency and inter-comparability of studies (Cowger et al., 2020). When sampling the water column from a boat using nets, samples should be taken from the side at a distance of 2–4 m to avoid turbulence from the bow or propeller mixing the MP particles (Mani et al., 2019; Skalska et al., 2020). It is also necessary to report the length of the net tow or the amount of time the net was deployed in the water column, as well as the length of time the pump was collecting water, for the experiment to be repeatable (Lusher et al., 2014; Cowger et al., 2020). When collecting benthic sediment with scoops or spades, a flow block/shield should be used to shield the collection area from the river flow, preventing fine debris and MPs from being washed out by the flow as the equipment is raised from the riverbed through the water column (Fripp and Diplas, 1993; Skalska et al., 2020). Studies that stated the required equipment dimensions, tow length/time, mesh/filter pore sizes, and employed appropriate deployment protocols were awarded two points, ensuring that the study's method was inter-comparable and reproducible. One point was given to studies that reported only subset of characteristics, used inappropriate deployment procedures or were restricted by the sampling equipment (e.g. sediment grab not being able to close properly due to coarse sediment grains). No points were awarded to studies that reported an insufficient description of sampling equipment and deployment methods, preventing the research from being replicated.

2.4.2.4. Criterion 9: sample size. As the true concentration of MPs in the river's water column and benthic sediment can never be fully determined, best efforts should be made to collect a volume of water or sediment that is representative of the river's size, geomorphology and MP concentration (Zhang et al., 2014). A sample size that is too small reduces the likelihood of finding MP particles and increases the margin of error in determining their presence. There is little research into representative and unbiased MP sampling for different sample locations or sampling equipment, so it is recommended that large sampling volumes are used, regardless of method choice, so that the uncertainty around the true MP concentration is reduced as much as possible, increasing the overall reliability of the study's results (Watkins et al., 2021). For sampling the water column, we use recommendations by Koelmans et al. (2019) that proposed a 500 L minimum sampling volume of water which would result in a representative sample of MPs. This suggestion was based on a systematic review of 30 surface water studies concentration data (including lakes, rivers and canals) ranging between 1×10^{-3} to 10 MP items/L, as well as detection limits for MP particles, which can be defined as the ability of the sampling methods to detect at least one MP particle with statistical confidence and accuracy (Koelmans et al., 2019).

It is understood that the MP concentration in a sample will be influenced by location, such as the proximity to wastewater treatment plants and the sampling equipment used, hence volumes should be adjusted to compensate for different factors which influence MP concentrations. For instance, a larger sample size is recommended for locations with lower MP concentrations, e.g. remote locations (Koelmans et al., 2019). The sample volume should be measured accurately to avoid miscalculation the MP concentration in the sample. For bulk and pump techniques, sample volume may be determined precisely based on the container used, but for net samples, flowmeters must be calibrated with the net opening area in order to estimate the sampling volume accurately (Watkins et al., 2021). A score of two was awarded to studies that sampled volumes of at least 500 L for the water column, while one point was awarded to studies that sampled <500 L due to limitation of the sampling equipment, e.g. clogging up of nets. Studies that sampled <500 L received a score of zero.

For sampling the riverine benthic sediment, while there is currently no minimum volume for a representative sediment sample, 400 g minimum volume per sampling point has been proposed by the National Oceanic and Atmospheric Administration of USA (NOAA) for marine research (Masura et al., 2015). However, a representative sample of benthic sediment for determining MP abundance will be a function of the riverbed grain size and grain sorting. For example, when sampling a gravel bed river ($d_{50} < 2$ mm) (Krumbein, 1934), a larger mass sample of sediment would be required to capture an appropriate representation of the fine sediment fraction. This would be determined by the vertical gradation of grain sizes and the conditions dictating whether or not an amour surface layer of higher coarse grains is present. However, because bed sediment grain size and grain sorting are rarely reported in MP studies, research into representative MP sample sizes is limited. Therefore, 400 g is proposed as a minimum sample mass for benthic sediment per sampling point with studies that sampled more than or equal to 400 g receiving two points, while studies that reported collecting <400 g due to sampling equipment limitations, e.g. sediment grab not being able to close properly due to coarse grain sediment reducing the mass sampled, receiving one point. Studies that collected <400 g received a score of zero.

2.4.2.5. Criterion 10: number of replicates. The replication of samples allows calculation of the standard deviation of results, reducing anomalous/erroneous data. Averaging across replicates increases the accuracy, reliability, and overall quality of the study. Replicates in water column samples includes a complete repeat of the entire sampling procedure taken immediately after the first sample at the same spatial location but next point in time. Integrative approaches to determine MP abundance in the water column, such as the "Rocket" encapsulated flow-through filtration device (Lenz and Labrenz, 2018) may overcome replication bias as multiple filtered samples are collected at one point in time. When collecting benthic sediment samples, an exact replication of the sampling procedure at the same spatial point is impossible due to the bathymetric and hydrodynamic variability in river system, thus 'replication' can only be taken in the form of spatial replicates very close to each other at the site. Studies that collected at least two replicate samples at each site or sampling date received two points. Studies that only took one replicate sample at each site or sampling date received one point, while studies that did not take/did not record repeat samples received zero point.

3. Results and discussion

3.1. Scoring of studies based on the MP sampling quality criteria

Each of the 36 selected studies was assessed against the ten quality criteria and a total score was provided, with a maximum possible score of 20 points. Results are presented in Table 2 with the studies listed in descending order of score from highest to lowest. It should be noted that the proposed MP sampling quality criteria does not examine each study's research aims or scientific findings, and solely relates to their reported sampling site details and sampling strategy.

Out of the 36 papers assessed, total scores ranged from 5 to 15, with water column studies (average total score of 10.5) scoring similarly to benthic sediment studies (average total score of 11.1). Scores across the first subset of criteria (maximum score of 10), *Sampling site details* (Section 2.4.1), ranged from 3 to 8, with average scores for water column studies of 5.5 and for benthic sediment studies of 5.0. Scores across the *Sampling methods and strategy* subset of criteria (Section 2.4.2) were slightly higher with scores ranging from 1 to 8, with an average score of 5 for water column studies and 6.1 for benthic sediment studies. It is worth noting that 35 of the 36 studies received a score of zero for at least one of the quality sampling criteria. This shows that there is some uncertainty in their data, which could lead to misinterpretation, lack of reproducibility, or difficulty in comparing with other studies. The top three criteria that achieved the

Table 2
Evaluation of the scores using the proposed MP sampling quality criteria obtained for each study reporting MP concentrations in the riverine water column and benthic sediment environment (n = 36 studies), ordered from highest to lowest total score.

	Sampling site details						Sampling methods and strategy						
	1	2	3	4	5		6	7	8	9	10		
Study	Catchment information	River physical properties	River hydraulic properties	Sampling point location	Temporal resolution	Average score for subset	Horizontal distribution of samples	Vertical location of samples	Collection equipment used	Sample size	Number of replicates	Average score for subset	Total score (max 20)
Water column studies													
Campanale et al. (2020)	2	0	1	2	2	7	1	2	2	2	0	7	14
Haberstroh et al. (2021)	1	1	2	2	2	8	1	2	1	2	0	6	14
Mani et al. (2015)	1	1	1	2	0	5	2	2	2	2	0	8	13
Dris et al. (2015)	1	0	1	2	2	6	2	2	1	2	0	7	13
Zhang et al. (2017)	1	1	1	2	2	7	2	2	2	0	0	6	13
Mintenig et al. (2020)	1	1	1	2	2	7	0	2	2	2	0	6	13
Wagner et al. (2019)	1	0	1	2	2	6	1	2	1	2	0	6	12
Eo et al. (2019)	1	1	1	2	2	7	1	2	2	0	0	5	12
Rodrigues et al. (2018)	2	0	1	2	2	7	0	1	2	2	0	5	12
Napper et al. (2021)	1	0	0	2	2	5	1	1	2	0	2	6	11
Lahens et al. (2018)	2	0	1	2	2	7	0	1	1	2	0	4	11
Chen et al. (2020)	1	0	1	2	2	6	1	2	1	0	0	4	10
Baldwin et al. (2016)	1	0	1	2	2	6	0	2	2	0	0	4	10
Sekudewicz et al. (2021)	2	1	1	2	0	6	1	2	1	0	0	4	10
Xiong et al. (2019)	1	1	1	2	0	5	2	2	1	0	0	5	10
Valine et al. (2020)	2	0	1	2	0	5	0	2	2	0	0	4	9
Liedermann et al. (2018)	0	1	1	1	0	3	2	2	2	0	0	6	9
Barrows et al. (2018)	1	0	0	2	2	5	1	0	2	0	1	4	9
Miller et al. (2017)	1	1	1	2	0	5	0	2	2	0	0	4	9
Kapp and Yeatman (2018)	1	0	1	2	0	4	1	2	1	1	0	5	9
Scherer et al. (2020)	1	0	1	2	0	4	1	1	1	2	0	5	9
Jiang et al. (2019)	1	0	0	2	0	3	0	1	2	0	2	5	8
Ding et al. (2019)	2	0	0	2	0	4	1	0	2	0	0	3	7
McCormick et al. (2016)	1	0	0	2	0	3	0	0	1	0	1	2	5
Average	1.2	0.4	0.8	2.0	1.1	5.5	0.9	1.5	1.6	0.8	0.3	5.0	10.5
Benthic sediment studies													
Hurley et al. (2018)	1	1	1	2	2	7	1	2	2	1	2	8	15
Gallitelli et al. (2020)	1	1	0	2	0	4	2	2	1	2	2	9	13
Eo et al. (2019)	1	1	1	2	0	5	1	2	1	2	2	8	13
Tibbetts et al. (2018)	1	1	1	2	0	5	1	2	1	2	2	8	13
Wang et al. (2018)	1	0	1	2	0	4	0	2	2	2	2	8	12
Niu et al. (2021)	1	1	1	2	0	5	1	2	2	0	2	7	12
Horton et al. (2017)	1	0	0	2	0	3	2	2	1	2	2	9	12
Nel et al. (2018)	2	1	1	2	2	8	0	2	0	2	0	4	12
Zhang et al. (2020)	1	1	1	2	0	5	1	2	1	0	2	6	11
Chen et al. (2020)	1	0	1	2	2	6	0	2	1	0	2	5	11
Corcoran et al. (2020)	2	1	1	2	0	6	1	0	2	0	2	5	11
Crew et al. (2020)	1	1	0	2	0	4	2	0	2	0	2	6	10
Ding et al. (2019)	2	1	0	2	0	5	1	0	1	0	2	4	9
He et al. (2020)	1	0	0	2	2	5	1	2	1	0	0	4	9
Huang et al. (2021)	1	0	0	2	0	3	1	2	1	0	2	6	9
Xiong et al. (2019)	1	1	1	2	0	5	1	0	0	0	0	1	6
Average	1.2	0.7	0.6	2.0	0.5	5.0	1.0	1.5	1.2	0.8	1.6	6.1	11.1

highest score of two were *Sampling point location* (criterion 4), *Vertical location of samples* (criterion 7) and *Collection equipment used* (criterion 8). Conversely, the most recurring criteria in which studies scored zero were *River physical properties* (criterion 2), *Number of replicates* (criterion 10), *Temporal resolution* (criterion 5), and *Sample size* (criterion 9).

3.2. Average score per criterion

3.2.1. Sampling site details criterion scores

An average score across each criterion was calculated to identify areas of sampling procedure that were performed well and those needing improvement.

Criterion 1, *Catchment information*, was well reported with mean scores of 1.2 for both water column and benthic sediment studies. Details of land use, and possible diffuse and point sources of MP pollution, were frequently reported, while studies often failed to include information regarding the catchment area, river properties or recent rainfall data. The absence of such information meant that the geographical scale of the study, overall study context in relation to the processes and factors which influence the flux of MP cannot be assessed. Studies that scored highly in this criterion documented factors that influence the variability of MP run-off, such as rainfall data, the weather conditions on the day of sampling, the season in which sampling occurred (wet or dry) or documented an average rainfall for the month of the sampling period compared to the yearly average. A good example of rainfall data reporting was a study on the Nakdong river where monthly rainfall data was correlated with the discharge of the river to assess the temporal impact rainfall and resulting run-off on the MP load in the river water column and benthic sediment, finding that the MP load was concentrated in the wet season by up to 81 % by MP weight (Eo et al., 2019).

Criterion 2, *River physical properties*, was the worst performed parameter of the ten criteria, with no studies achieving a score of two and on average scored less than one (mean scores: water column = 0.4, benthic sediment = 0.7) indicating that this aspect of the sampling process needs significant attention in future field campaigns. Studies often failed to include any of the river dimensions (i.e. mean width or mean depth) or the longitudinal bed slope which meant that the study context in terms of cross-sectional information, river energy slope, and a more in-depth understanding of the river hydraulics and MP transport dynamics, cannot be evaluated. Only half of benthic sediment studies recorded the benthic sediment characteristics, in which the river grain size was either categorised by type, e.g. silt, sand or gravel, or grouped according to the median grain size diameter (d_{50}). This property partially determines whether a MP particle remains on the riverbed or is remobilised and entrained into the river flow due to the relative shielding by the riverbed grains (Waldschläger and Schüttrumpf, 2019b). A study on the Mignone river (Italy) provided a good example of reporting the grain size of the riverbed by documenting the average grain size of each riverbed sampled and then categorising each sampling point based on their percentage of each grain size, ensuring that the riverbed characteristics were recorded for each sampling point (Gallitelli et al., 2020).

For *River hydraulic properties* (criterion 3, mean scores: water column = 0.8, benthic sediment = 0.6), studies often reported the average velocity measurement for the entire river, providing a score of one, but failed to report these characteristics between separate sampling points or over the sampling period which, would provide a score of two. Variations in velocity will affect the MP concentrations between sampling points in both the water column and benthic sediment, increasing the study's uncertainty if not disclosed. River discharge was mostly reported well for both water column and benthic sediment studies. A good instance of this criterion was a study conducted on a 820 km reach length of the Rhine river (Germany) which reported the velocity and discharge between sampling points, as well as the difference in discharge to annual base flow conditions which allowed the study to relate MP concentrations in the water column to flow conditions (Mani et al., 2015).

The criterion *Sampling point location* (criterion 4) was the only parameter to receive a full average score of two for both the water column and benthic sediment, indicating that the majority of studies met this criterion. Studies scored well probably due to the ease of using mobile phones with GPS or apps that are available to collect this data, e.g. ArcGIS collector, or inclusion a map of an equivalent spatial resolution.

Results show that water column studies met the requirements of criterion 5, *Temporal resolution*, with a mean score of 1.1. All water column studies either achieved a score of two or zero, with no studies including a reasonable justification for their one point in time approach. Only four of the 12 benthic sediment studies examined the temporal variability of MPs in the benthic sediment showing statistically significant temporal variability in MP abundance in benthic sediment samples (Hurley et al., 2018; Nel et al., 2018; Chen et al., 2020; He et al., 2020). This suggests that benthic sediment MP temporal resolution may be understudied in MP literature, despite the fact that MP abundance has been demonstrated to be highly dependent on sampling period in terms of wet or dry seasons. For example, lower MP concentrations in benthic sediment were observed during the dry months of the year (6.3 ± 4.3 MP item/kg) in the Bloukrans river (South Africa), while significantly higher concentrations were found during the wet months (160.1 ± 139.5 MP items/kg) (Nel et al., 2018).

3.2.2. Sampling methods and strategy scores

For criterion 6, *Horizontal distribution of samples*, both water column and benthic sediment studies often failed to report the specific location at which the samples were taken on the river's width or used non-technical terms, e.g. mid-channel and banks, resulting in low average scores (mean scores water column = 0.9, benthic sediment = 1). For instance, Ding et al. (2019), Huang et al. (2021) and Sekudewicz et al. (2021) described the horizontal distribution of samples as the right, left and centre sections of the river, which does not provide enough information about the interactions the sample location may have with the riverbanks. Due to the inherent heterogeneous distribution of the flow velocities across the river's width, e.g. owed to its morphology or due to secondary currents, observed MP concentrations will vary significantly depending on sample location across the width of the river section. Such information should therefore be reported accurately using specific measurements of the sampling locations relative to the true right- and left-hand sides of the riverbank when looking in the downstream direction of the flow.

In criterion 7, *Vertical location of samples*, both water column and benthic sediment studies scored an average of 1.5. However, studies often still used ambiguous terminology, e.g. 'surface waters' or 'the top layer of benthic sediment', to characterise vertical elevation that provided a score of one, rather than the exact depth at which samples were taken which scored two. Research disciplines may interpret this terminology differently as reference to various depths in the water column or benthic sediment, highlighting a level of data uncertainty. For instance, 'surface waters' was described as the top 0–0.5 m by Napper et al. (2021), while Mintenig et al. (2020) described it as the upmost 0.05 m of the water column. This is critical information for the understanding of suspended load transport of MPs and the vertical distribution of different MP polymers, shapes and sizes.

Criterion 8, *Collection equipment used*, scored well overall with mean scores for water column and benthic sediment of 1.6 and 1.2, respectively. Most studies reported the mesh/filter pore size used and the type of sampling equipment deployed. For water column studies these included manta nets, neuston nets, plankton nets, drift nets, trawl nets AVANI nets, large flow sampler pumps, centrifugal water pumps, motor water pumps, submersible water pumps, metal buckets, stainless steel beakers and glass jars. In the benthic sediment studies van Veen grabs, Petite Ponar grabs, Ponar grabs, grab buckets, Peterson grabs and cylindrical sediment grabs, stainless steel scoops, stainless steel shovels, and corers were used. However, some studies failed to report the dimensions of the sampling equipment, e.g. net opening area used to sample the water column or the size of the grab area used to sample the benthic sediment, which reduces its repeatability. Furthermore, studies commonly omitted details regarding the tow length or tow time of net samples without an appropriate deployment of the sampling equipment such as deploying nets at 2–4 m away from boat using a flow block/shield to prevent MPs from being washed out by the flow as the equipment is raised from the riverbed, lowering the average score for this criterion. The absence of these details decreases the transparency of the studies sampling procedures reducing its reliability (Cowger et al., 2020).

A mean score of 0.8 was achieved for both the water column and benthic sediment studies for criterion 9, *Sample size*. Studies often sampled less than the recommended volumes of water and sediment mass (Koelmans et al., 2019). A too small sample size may decrease the likelihood of detecting MP particles or result in an overestimation of MP abundance. For example, Lahens et al. (2018) reported abundances as high as 172,000–519,000 items/m^3 in the water column based on a bulk sample size of 300 mL where only 51–140 MP items were observed.

Criterion 10, *Replication of samples*, in the water column was poorly conducted (mean scores: water column = 0.3) with only three studies taking one or more replicate samples immediately after the first one at the same spatial location per sampling point or sampling date. 11 water column studies took spatial replications at each sampling point, however, due to variability in the hydrodynamic flow field in the river, MP concentrations may differ significantly between replicates and are therefore not considered true replicates of the sample. Generally, for benthic sediment studies, at least one replicate sample was taken during field work (mean scores: benthic sediment = 1.6). A range of replication approaches were used, for example, Horton et al. (2017) and Tibbetts et al. (2018) took four replicate benthic sediment samples of 250 g (1 kg in total) taken at 1 m intervals along a 3 m transect which was parallel to the riverbank at 1 m distance,

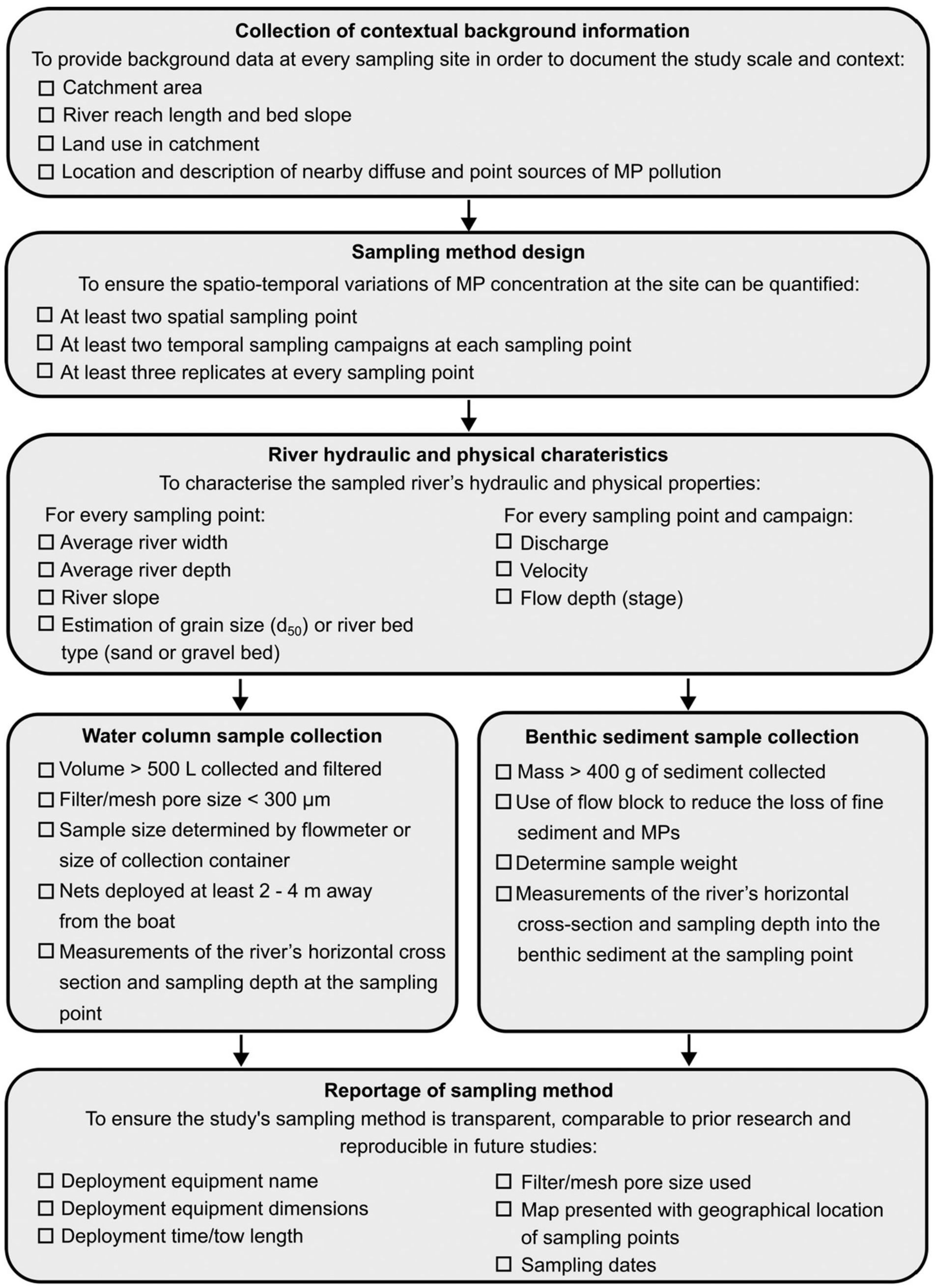

Fig. 1. An idealised sampling approach checklist that can be used by researchers as a framework for conducting a harmonised and high-quality sampling approach by ensuring the study is inter-comparable and the variables underpinning MP transport in rivers are reported. Adherence to the checklist assures that a study's sampling procedure receives the maximum score for each quality criterion (Table 1).

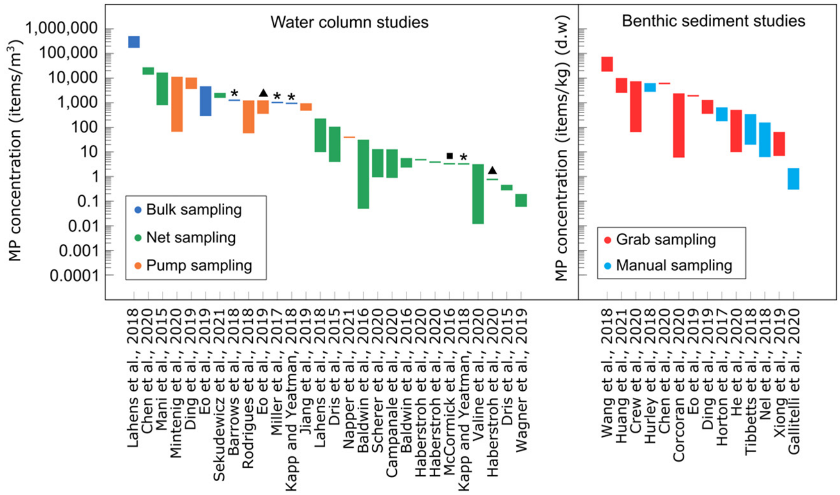

Fig. 2. Reported MP concentrations found in the water column and benthic sediment (dry weight), categorised by their sampling method from 33 of the 36 selected studies. Boxes represent the range of MP concentrations reported (minimum and maximum) and dashes represent the mean MP concentration found if a range was not presented. Some references presented two concentration ranges in the same study depending on the sampling equipment deployed or section of the water column sampled. Lahens et al. (2018) determined MP concentrations separately for fragments using a net, and fibres using bulk sampling techniques. Star symbols (*) indicate that the study also found concentrations of 0 MP items/m^3 at some of their sampling sites. Triangle symbols (▲) indicate samples were taken from the reported 'middle water column' and square symbols (■) indicate samples were taken from the reported 'bottom water column'. Data from three studies where unit conversion into items/m^3 or items/kg was not possible are not included in the figure.

while Ding et al. (2019) took three sediment samples on the middle, left and right sides of the same river cross-section. The greater adherence to the criterion by riverbed sediment studies compared to water column studies could be related to the relative ease with which grab or manual samples of benthic sediment can be replicated, as opposed to replicating net tows or pump samples that require manual cleaning and emptying of nets and filters.

3.3. Idealised MP sampling approach

To improve and harmonise current sampling approaches for MPs in the water column and benthic sediment, we present an idealised sampling procedure checklist, shown in Fig. 1, that if followed, would result in a study receiving the maximum score of two for each quality criterion (Table 1). The idealised sampling procedure is divided into five sections: collection of contextual background information, sampling method design, characterisation of the sampled river, sample collection and reportage of sampling method. Adhering to the idealised sampling approach will ensure that a study documents the necessary information to allow MP concentrations to be correlated with land use, pollution sources, weather conditions, and the physical and hydraulic properties of the river. Researchers can use the checklist in the design of their sampling approach, while stakeholders can use it to develop standardised MP monitoring campaigns.

3.4. Meta-analysis of MPs in riverine environments

3.4.1. MP concentrations in rivers

A meta-analysis on the reported MP concentrations in MP items/m^3 sampled from the water column, and MP items/kg from benthic sediment is presented in Fig. 2, in log scale, categorised by sampling method. The data does not account for the precise horizontal position of sample location within the cross-sectional transect, as this is rarely provided, as higher concentrations may be found near the riverbanks and in lower velocity areas (Section 2.4.2.1). MP concentrations in the water column ranged over seven orders of magnitude from 1.2×10^{-2} to 5.19×10^{5} MP items/m^3, with three studies finding no MP concentrations in some of their water column samplings. Concentrations in the riverine benthic sediment ranged five orders of magnitude from 3×10^{-1} to 7.48×10^{4} MP items/kg.

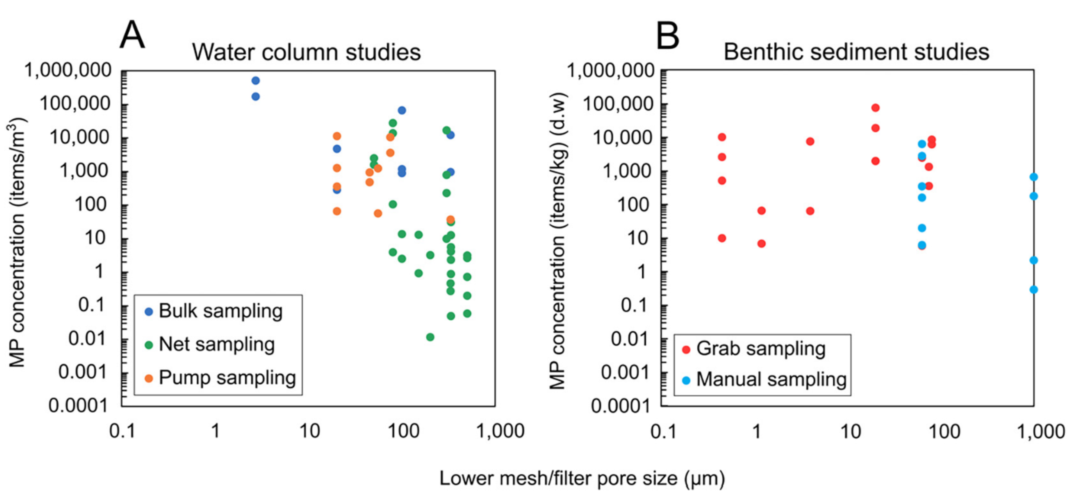

Fig. 3. MP concentrations for different mesh/filter pore sizes used for sampling or isolating the MPs from the A) water column and B) benthic sediment, categorised by the sampling equipment used.

The large variations in MP concentrations in both the water column and benthic sediment may be attributed to the sampling approach and equipment (Coverton et al., 2019; Lindeque et al., 2020). Sampling the water column using bulk and pump sampling generally gives a higher order of MP concentration, compared to net sampling. In addition, MP concentrations in the benthic sediment are slightly higher for studies which deploy grabs compared to those that used manual sampling, albeit this is based on a small number of studies (benthic sediment $n = 12$). The sampling location's proximity to known point and diffuse sources of MPs, e.g. wastewater treatment plant effluent and urban land usages, will also impact the MP concentrations (McCormick et al., 2014; Wagner et al., 2019). Furthermore, the timing and positioning of sampling in relation to spatio-temporal factors, such as rainfall events backwater pool or recirculation zones, will also cause large differences in MP concentrations (Hurley et al., 2018; Corcoran et al., 2020; Wong et al., 2020). The multitude of factors that can affect MP concentration highlight the difficulties in determining the dominant anthropogenic and natural mechanisms that impact MP abundance variation between studies, making it challenging to interpret an overall picture of MP pollution concentrations in freshwater riverine environments.

3.4.2. Lower size limits for MP detection

At present, there is no defined lower size limit for the detection of MP particles, which is usually determined by the mesh/filter pore size used during the sampling or isolation of MPs (Frias and Nash, 2019; Prata et al., 2019). Fig. 3 shows the observed MP concentrations for both the water column and benthic sediment studies, in log scale, and the lower mesh/filter pore size used during sampling or isolating the MPs. 300–330 μm net mesh pore sizes were used in 9 of the 20 water column studies, enabling a direct comparison between these studies and indicating the start of some standardisation of methods. For water column studies, a higher MP concentration is observed with the use of a finer mesh/filter pore size. Indeed, in a study where water column sample replicates were conducted with two different net mesh pore sizes (namely 100 μm versus 330 μm), the smaller mesh recovered about 30 times more MP items/m^3 compared to larger mesh size (Dris et al., 2015). A smaller mesh/filter pore size is associated with pump sampling compared to net sampling, with the most common pore size used for pumps of 20 μm while for nets was 333 μm. Bulk samples are usually processed and filtered in the laboratory, with the most common filter pore size being 100 μm. Therefore, MP concentrations are expected to be directly related to the mesh/filter pore size of the sampling equipment deployed to measure MP abundance in the water column. This emphasizes the importance of documenting the mesh/filter pore size of collection equipment when making inter-comparisons between studies, as well as the impact equipment may have on the observed MP concentration.

For the benthic sediment no correlations were found between the observed MP concentrations and mesh/filter pore size used to isolate them from the sediment matrices (Fig. 3b). It would be expected that the use of a finer mesh/filter would yield higher MP concentrations, although this is not shown here through the 14 sediment studies.

The recovery of MPs larger than 1 mm from sediment matrices is relatively easy as particles can be manually sorted and verified with chemical analysis, and hence the majority of the data relates to particles >1 mm. However, a number of studies have reported that the laboratory methods used to recover MPs from sediments are bias towards larger particles. Small MPs (<1 mm) may be lost during the pre-treatment stages of extraction or are not completely separated from the sediment matrices (Fuller and Gautam, 2016; Yang et al., 2021). For example, using a zinc chloride density separation and stirring the solution to isolate the MPs from the sediment matrices, which was the method used in six out of the 12 selected benthic sediment studies for this meta-analysis, only recovered around 40 % of MPs particles <1 mm (Imhof et al., 2012; Ivleva et al., 2017). Results can then be skewed towards larger MP particles, with small MPs likely not identified in the sample, thus potentially leading to an underestimation of the overall benthic MP concentration.

3.4.3. Sample volume

The observed MP concentration from the 36 studies against the sampling volume for the water column and benthic sediment are shown in Fig. 4. For the water column, studies which had a lower sample volume tended to observe a higher MP concentration. However, the sample volume is also seen to be a function of the sampling equipment. As discussed in Section 3.3, certain sampling equipment (bulk, net or pump) are associated with different mesh pore sizes which determine the lower size limits for MP particle detection, and therefore the amount of MP analysed in the sample. A similar relationship was observed in a study that compared the sample bias between sample volume, sample method, filter/mesh pore size and MP concentration observed in 118 marine and freshwater studies (Watkins et al., 2021). In terms of the benthic sediment, the sample size seems to have no influence over the observed MP concentration, although it is still recommended that a large sample size to be used to present a true reflection of MP concentrations in the benthic sediment.

3.4.4. MP size intervals

A total of 21 from the 36 studies categorised the sampled MP size distribution and reported the number of particles observed per size interval, as shown in Fig. 5. MP size intervals are not standardised and a range of MP size intervals were used depending on each individual study's findings, mesh/filter pore sizes used and lower size detection limit for the MP particles. For example, Jiang et al. (2019) and Ding et al. (2019) reported MPs in size intervals in terms of <500 μm, 1000–2000 μm, 2000–3000 μm,

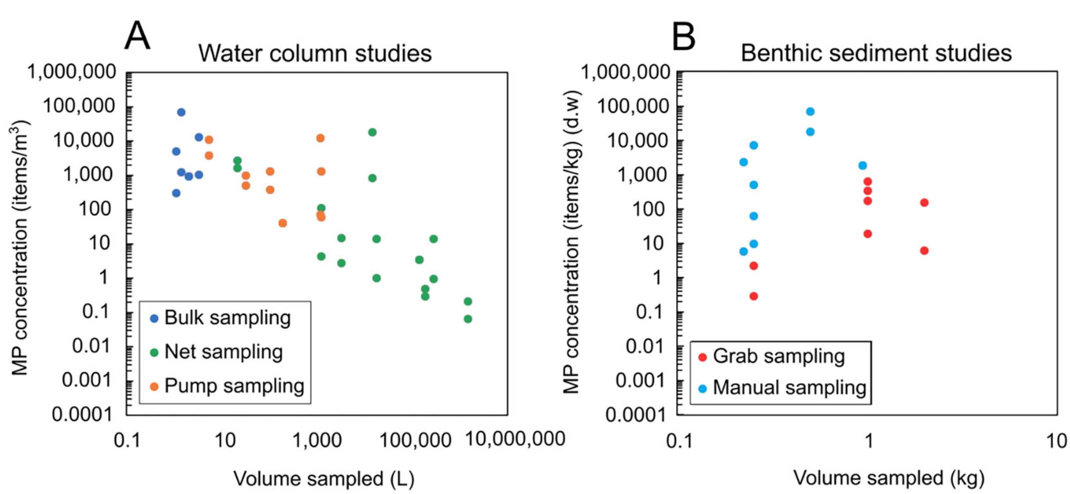

Fig. 4. The observed MP concentrations for different sample volumes from the A) water column and B) benthic sediment, categorised by the sampling equipment used.

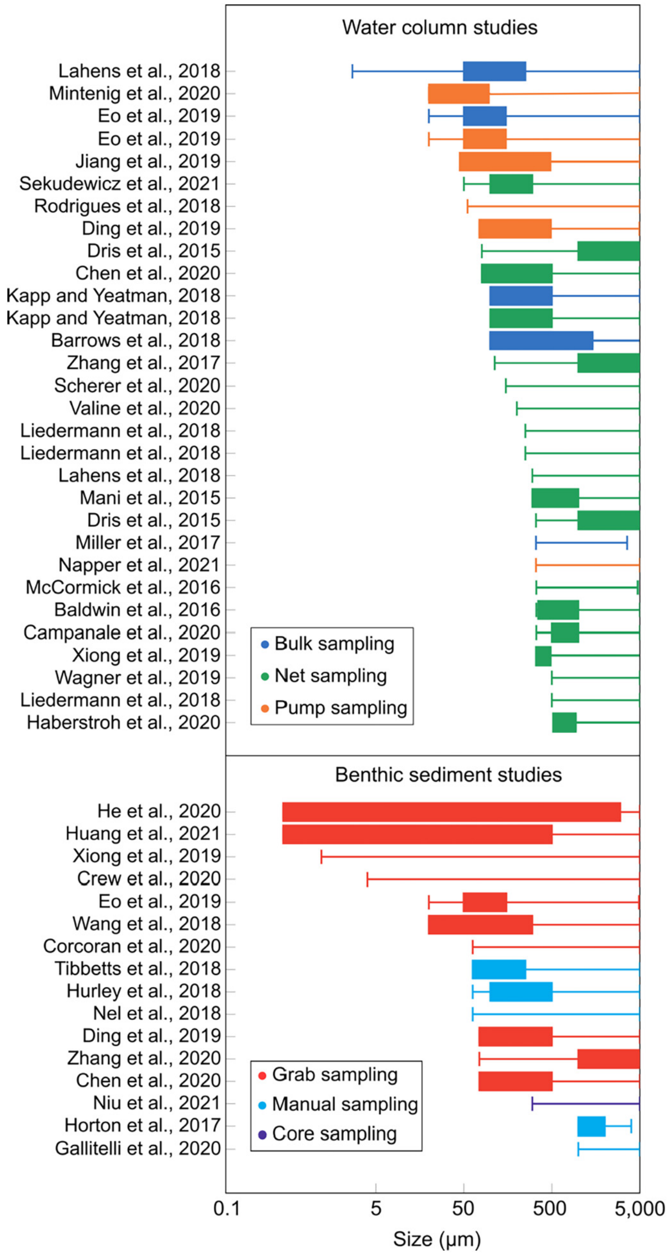

Fig. 5. Target size range used for MP sampling in the riverine water column and benthic sediment from all 36 selected studies. Whiskers display the lower and upper size limit of MP retention used for sampling per study. Boxes display the most frequent size interval observed in the study. If the upper size limit was not reported in the study, it was assumed to be 5000 μm as this is the defined upper size limit for MPs. Dris et al. (2015) and Lahens et al. (2018) only provided size distributions for fibre MPs. Some studies reported two target size ranges depending on the sampling equipment deployed.

3000–4000 μm and 4000–5000 μm, while Kapp and Yeatman (2018) used intervals of 100–500 μm and 100–300 μm to report the observed MPs. This hinders the meta-analysis of the size distribution that can be performed as size intervals were not uniform between studies.

Generally, data showed that the smallest MP size range used by both water column and benthic sediment studies were the most commonly detected in the samples, implying that small MPs may be the most abundant MPs in riverine environments which is consistent with previous freshwater and marine studies (Lu et al., 2021; Niu et al., 2021; Palmer and Herat, 2021). This is thought to be due to larger MPs continually fragmenting into a number of smaller MPs overtime due to biological, mechanical and chemical breakdown (Andrady, 2011; Lambert and Wagner, 2016; Yuan et al., 2020). This implies that with decreasing MP size, an increased concentration is likely to be observed, which is similar to conclusions from other freshwater and marine studies (Wright et al., 2013; Kooi and Koelmans, 2019; Lindeque et al., 2020). These results emphasize the importance of employing sampling equipment capable of detecting small MPs to avoid sampling bias and underestimating MPs concentrations.

3.4.5. MP polymers reported in riverine environments

17 different types of plastic polymers were observed in the water column and benthic sediment samples from 28 out of the 36 studies. The occurrence of the top ten most frequently observed polymers with their specific densities are presented in Fig. 6a, which included polypropylene (PP), polyethene (PE), polystyrene (PS), polyethylene terephthalate (PET), polyvinyl chloride (PVC), acrylic, polyamide (PA), polyurethane (PU), polyvinyl alcohol (PVA), and polyacrylonitrile (PAN). The top five polymers reflect the global demand for plastic polymers in the following order: PE > PP > PVC > PET > PS (Geyer et al., 2017). Other plastics were less commonly reported that agrees with previous reports, some being potentially sourced from plastic pipes (PVC), synthetic fabrics (acrylic and PA), foams (PU), food packaging (PU) and paints (acrylic) (Andrady, 2011, 2017; Hamid et al., 2018).

The data here only consider the acknowledgement of these polymers in each evaluated study, which means that their occurrence frequency was not accounted for in this meta-analysis. The distribution of polymers in the water column and benthic sediment would generally be expected to reflect their specific densities, with polymers less dense than water (1 g/cm^3) (PP and PE) reported more commonly floating near the surface of the water column, and polymers denser than water (PS, PET, PVC, PA, PU, PVA and PAN) found mostly in benthic sediment samples (Hidalgo-Ruz et al., 2012; Andrady, 2017). However, results show a more variable distribution. PP and PE, polymers with densities lower than 1 g/cm^3, were reported in a high percentage of water column studies but were still frequently observed by studies sampling the benthic sediment. Conversely, polymers with densities >1 g/cm^3 (e.g. PET, PVC and acrylic) with a larger potential settling velocity, were found in a high percentage of benthic sediment studies, although were still commonly observed in water column studies. PS (density of 1.04–1.1 g/cm^3) was found more often in the water column than in the benthic sediment probably due to the fact that it is normally injected with air to produce expanded PS foam (EPS), rendering it is less dense than water and allowing it to float (Lenaker et al., 2019).

The variable distribution of MP polymers observed in the riverine ecosystem may be attributed to the remobilisation potential of MP particles from the benthic sediment to the water column. Field and laboratory studies have shown that high flow events, with high bed shear stresses, can exceed the threshold of motion required for dense MPs to move from the benthic sediment into the water column, which may account for the observed increased concentrations of polymers with densities larger than 1 g/cm^3 in the water column (Hurley et al., 2018; Waldschläger and Schüttrumpf, 2019b; Haberstroh et al., 2021). The remobilisation and entrainment of MPs from the riverbed into the water column partially depends on the riverbed grain size, as larger sediment grains protruding out of the bed may shelter the MP particle from the flow, thus requiring higher bed shear stresses to trigger MP suspension (Fenton et al., 1977; Waldschläger and Schüttrumpf, 2019b). The description of the hydraulic characteristics, the bed shear stresses, and bed grain characteristics is scarce in MP literature, making it difficult to draw any evidence on the whether some polymers have a higher probability of being remobilised into the water column compared to others.

Conversely, MPs in freshwater environments may become naturally biofouled as a result of colonising microorganisms, or become aggregated with organic and inorganic cohesive particles such as silts, clays and iron oxides (Drago et al., 2020; Kim et al., 2021; Miao et al., 2021). These processes may increase the size and specific densities of MP particles and promote their sinking to the riverbed, which may explain why polymers with a density of approx. 1 g/cm^3 were found in benthic sediment samples (Besseling

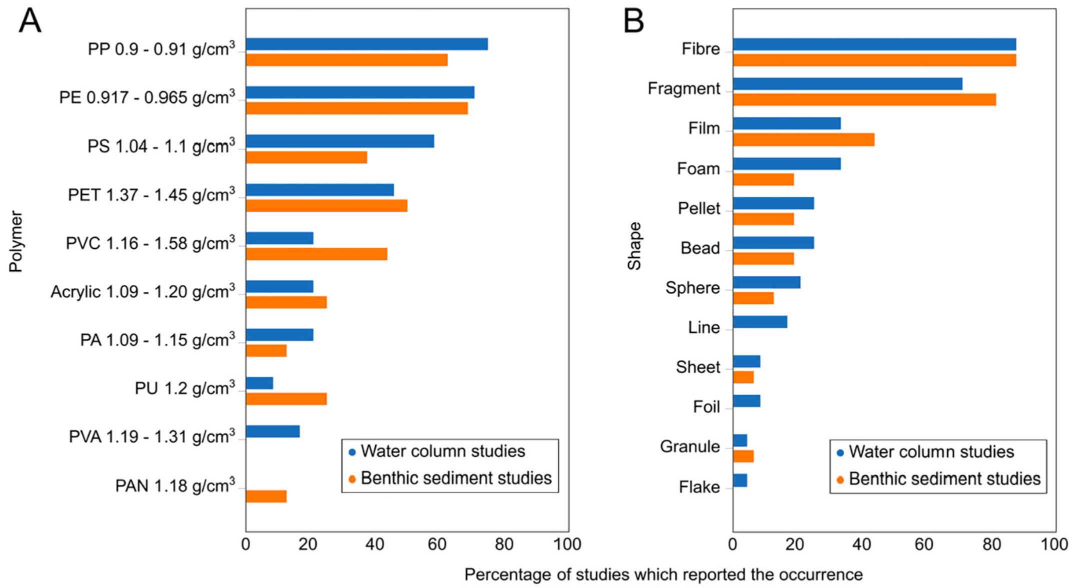

Fig. 6. The percentage of studies reporting the occurrence of a particular A) Polymer, displayed by their specific densities (from a total of 28 studies out of 36) and B) Shape (from a total of 32 studies out of 36) in the riverine water column and benthic sediment (excluding those studies that did not report MP polymer and shape).

et al., 2017; Chen et al., 2019; Leiser et al., 2020). Laboratory studies have shown that the presence of biofilms on the surface of PS MP particles increased settling velocities by 16 % in estuarine water and 81 % in marine water (Kaiser et al., 2017). Similar biofouling processes are thought to occur on freshwater MPs (Besseling et al., 2015; Chen et al., 2019; Miao et al., 2021). At present, it is difficult to evaluate the interactions of biofilms and aggregated MP particles may have on MP transport in rivers due to a lack of field and laboratory data.

3.4.6. MP shapes reported in riverine environments

12 MP shapes were identified in 32 out of the 36 studies, with the occurrence of each shape provided in Fig. 6b based on their acknowledgement in each study. Terminology used to classify MP shape is not standardised across the MP community and details regarding the description and dimensions of MP shape class is also sparse (Hartmann et al., 2019). As a result, terms used to classify MP shape, e.g. ‘sheets’, ‘granules’, ‘flakes’ and ‘foils’, can be ambiguous without actual physical dimensions. MP shape classes may also fall into different subcategories, for example, the term ‘fragment’ may include any MP particle that has fragmented from a larger plastic item, e.g. ‘foams’, ‘films’ and ‘flakes’. However, a generalised estimate of shape distribution based on recommendations of the classification by Hartmann et al. (2019) is presented with the most common shapes found in the riverine ecosystem being; irregular particles (‘fragments’, ‘foams’, ‘granules’, ‘flakes’), fibres (‘fibres’ and ‘lines’), spheres (‘pellets’, ‘beads’ and ‘spheres’), and films (‘films’, ‘sheets’, ‘foils’).

The percentage of studies which observed the occurrence of irregular particles (‘fragments’, ‘foams’, ‘granules’, ‘flakes’), fibres (‘fibres’ and ‘lines’), spheres (‘pellets’, ‘beads’ and ‘spheres’), and films (‘films’, ‘sheets’, ‘foils’) were similar between studies that focused on the water column and benthic sediment. Laboratory settling velocity experiments have found that the particle shape and other intrinsic physical properties, such as size and density, can influence MP deposition on the benthic sediment. Previous studies have demonstrated that fibres may remain suspended in the water column longer than spheres and irregular particles due to their larger relative surface area and irregular settling movements which slow their settling velocity down (Khatmullina and Isachenko, 2017; Waldschläger and Schüttrumpf, 2019a). As a result, spheres and irregular particles may settle and accumulate in riverine benthic sediment faster than fibres, as their settling velocities are larger, however, the result of the meta-analysis does not follow this pattern. Most laboratory studies often use a homogeneous mixture of virgin plastic, which does not relate to the diversity of MPs found in field settings (Skalska et al., 2020). Furthermore, biofouling and aggregation with cohesive sediment particles and microorganism are not currently considered in laboratory studies and may be dominant factors determining the vertical distribution of MP particles (Besseling et al., 2017; Chen et al., 2019; Leiser et al., 2020).

4. Conclusions

This paper presents a set of criteria to inform robust field procedures for sampling MPs in the water column and benthic sediment of the riverine environment to ensure that the data reflects the complex fluvial variables underpinning MP distribution, while adhering to data quality objectives in terms of representability, comparability and completeness. A total of 36 MP papers were scored against the MP sampling quality criteria and indicated that a good number of studies report the spatial information of sampling sites, vertical location of samples, and the sampling equipment used. However, limited studies included key information about the sampling site's physical and hydraulic properties or omitted information related to sample size and temporal resolution of samples, with at least six out of the ten aspects of sampling quality criteria needing improvement in order to ensure data quality standards are met. An idealised sampling approach is presented, which if followed would ensure that studies receive the maximum score for each quality criterion and that harmonised sampling procedures are practiced in the future within the research community.

A meta-analysis of the 36 selected studies revealed that MP concentrations differed widely in the water column and benthic sediment, and this is not necessarily a true reflection of reality. Future research should be cautious about the interpretation of water column MP concentration data due to bias towards higher MP concentrations when sampling with bulk methods and with a finer mesh/pore size, which may lead to misinterpretation of MP abundance. No sampling bias was observed for benthic sediment studies. It is recommended that sample sizes as large as possible should be used, regardless of sampling equipment, to reflect true concentrations of MPs. PP, PE, PS, PET, PVC were the most reported MP polymer, while irregular particles, fibres, spheres and films were the most frequently reported in both the water column and benthic sediment. Polymer abundances were different from their expected distributions based on their intrinsic physical properties such as density and settling velocity, indicating that other mechanisms are at play such as the hiding-exposure effect, and aggregation with biofilms and other suspended solids.

The sampling quality criteria and idealised sampling approach proposed here can be used as guidelines to improve MP sampling procedures in the freshwater environment which can be employed by researchers and stakeholders to develop a standardised MP monitoring framework, as well as by policymakers evaluate the quality of field data. The use of the sampling quality criteria will enhance the inter-comparability of MP research to develop a more accurate global picture of MP abundance and distribution in the riverine environment.

CRediT authorship contribution statement

J. Lofty: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Validation. **P. Ouro:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Validation, Supervision, Funding acquisition. **C.A.M.E. Wilson:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Validation, Supervision, Funding acquisition.

Data availability

Data will be made available on request.

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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