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ADVANCED REVIEW

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A review on microplastics in major European rivers

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Abstract

The topic of riverine microplastics is of great interest to the general public, yet the univocal scientific knowledge on this topic is limited. This review investigated the occurrence of microplastics in 6 major European rivers and their tributaries based on the results from 29 studies. We examined the reviewed studies in regard to data quality and reproducibility and assessed the abundance of microplastics in different sections of the water column. Furthermore, we investigated the chemical composition and potential origin of the reported riverine microplastics. We found that polystyrene, polypropylene, and polyethylene were the most abundant polymer types. The majority of primary microplastics arose from the industry sector as well as from personal care and cleaning products, whereas secondary microplastics constituted fibers from synthetic textiles and fragments of diverse origins. We highlighted the diversity of experimental and analytical approaches that could lead to high uncertainties in the measurements of microplastics abundance. Furthermore, the presence of microplastics in rivers was found to vary spatially likely due to point and nonpoint pollution sources of anthropogenic activities. Heterogenous environmental processes impacted the fate of microplastics characterized by various forms, sizes, and densities, in different ways. This impeded the identification of representative quantitative measurements of microplastics across different time frames. We advocate for the development of standardized protocols by the research community to ensure higher reproducibility of sampling, processing, and analysis of microplastics in aquatic environments. We recommend long-term and site-specific monitoring on microplastics with high data comparability to better inform policy making.

This article is categorized under:
Science of Water > Water Quality
Water and Life > Conservation, Management, and Awareness

KEYWORDS
data quality, environmental monitoring, European river, microplastics

1 | INTRODUCTION

The mass production of plastic materials has been booming since their invention in the 1940s (Carpenter & Smith Jr, 1972; Cole et al., 2011) with future production and utilization projected to increase worldwide (Porta, 2021). Plastic debris is ubiquitous and can be found in many environments (Bergmann et al., 2019; Jamieson et al., 2019; Ren et al., 2021) as a result of mismanagement of plastic waste (Ferronato & Torretta, 2019), technical limitations of municipal and industrial wastewater treatment processes (Luo et al., 2023; Sun et al., 2019) and gradual deterioration of the materials (Biber et al., 2019; Boucher & Friot, 2017). Plastic debris is characterized by high stability and durability (Hohenblum et al., 2015) which enables it to persist for long periods of time, ranging from hundreds of years (Fath, 2019; Hohenblum et al., 2015) to several thousand years (Bertling et al., 2022; Fath, 2019). Furthermore, dynamic natural processes fragment and spatially redistribute plastic contaminants (Bajt, 2021; Lehmann et al., 2021; van Emmerik & Schwarz, 2020), while living organisms ingest and transfer them along the food chain (Bajt, 2021; Rogers et al., 2020). As a result, plastic debris is posing a serious threat to the Earth's ecosystems (de Souza Machado et al., 2018; Leslie et al., 2017), and more in-depth scientific knowledge on this topic is urgently needed.

Plastics debris ranging in size from 1 μm to 5 mm are often defined as microplastics (Frias & Nash, 2019; van Wijnen et al., 2019). Microplastics are expected to have long-lasting and significant effects on the environment in comparison to other forms of plastic debris (de Souza Machado et al., 2018). However, their fate in the environment is complex and largely unpredictable (Besseling et al., 2017). Thus, microplastics have attracted a growing scientific interest with the number of academic contributions on the topics rising sharply in the last 5 years (Figure 1). Marine microplastics, in particular, have been monitored in recent time with field measurements giving rise to a number of national and international databases (NOAA/NCEI, 2022). In contrast, the occurrence of microplastics in freshwater systems has not been investigated in such detail and fewer monitoring tools are available (Čerkasova et al., 2023; Zhang et al., 2023). This results in a lack of knowledge about the abundance and distribution of microplastics in freshwater bodies. Under the influence of the high spatiotemporal heterogeneity of the generation and emission of microplastic wastes, and because of the dynamic and different hydrological conditions of the river watersheds, estimations of the riverine microplastics emissions that are based on empirical measurements and models vary largely among studies for two to three orders of magnitudes, which causes high uncertainties (Zhang et al., 2023).

At present, there is a significant gap in knowledge regarding the abundance and distribution of microplastics in freshwater bodies, especially in the European context. In this paper, we reviewed scientific literature to evaluate and compare the state of microplastic contamination of six major European rivers. Our aims were to (1) assess data quality of the selected studies; (2) quantify the microplastic concentration found in surface water, suspended particulate matter, and river sediments; and (3) identify the most common polymer types. We have also investigated potential sources of microplastics in European rivers. Based on this review, we provided recommendations for future research and policymaking.

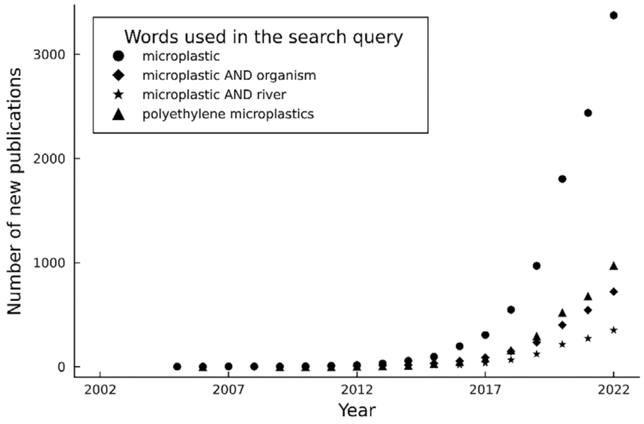

FIGURE 1 Number of scientific publications about microplastic studies (the search was performed on PubMed, and "polyethylene microplastics" was chosen for the search query because of the high abundance of this polymer type in riverine environments, see Figure 4).

2 | REVIEW DESIGN

2.1 | Selection of studies

The review of literature was performed in the Google Scholar Search Engine in March 2023. The initial step of literature identification included the search terms "microplastics" AND "the name of a European river (e.g., Rhine, Danube, Elbe, etc.)", which could be in the title, abstract, and/or keywords. Rivers were included when at least three research articles or official reports with data that were independent from one another were published (by the end of 2022). A complete list of rivers selected for this review is available in Appendix S1. Six European rivers, that is, Rhine, Danube, Elbe, Po, Thames, and Vistula, and their tributaries were investigated. In total, 29 studies underwent a full-text assessment and information on the experimental design (including the processes of sampling and analysis), the abundance, and the characteristics of riverine microplastics were evaluated.

2.2 | Data analysis

2.2.1 | Data quality assessment of the selected studies

The data quality of the selected studies was assessed using the criteria and the scoring system developed by Koelmans et al. (2019). Each study was evaluated in terms of the following criteria: (1) sampling methods, (2) sample volume or mass, (3) sample processing and storage, (4) laboratory preparation, (5) clean air conditions, (6) negative control, (7) positive control, (8) sample treatment, and (9) polymer identification—all with the aim to quantify the degree of reproducibility and reliability.

2.2.2 | Microplastic concentrations

The specifications of microplastic content were converted into two different units, that is, particles/m^3 and particles/kg. The former allowed for quantification of microplastics in the water phase and the latter in the solid matrix (i.e., sediment or suspended particulate matter). The representativeness of the volume and/or mass of samples was tested against criteria by Koelmans et al. (2019). Measurements from five studies were excluded because representative volume and/or mass of samples was not collected (see Devereux et al., 2022; Horton et al., 2017; Kaliszewicz et al., 2020; Lechner et al., 2014; Sekudewicz et al., 2021). Similarly, particle numbers and concentrations estimated based on extrapolations were excluded (see Mughini-Gras et al., 2021). One measurement in a lake in the study by Fath (2019) and measurements of river estuary samples in all studies were excluded as well. In total, 14 (out of 29) studies with high-quality measurements of microplastic concentrations were analyzed.

2.2.3 | Polymer types

To determine the polymer type of riverine microplastics, 18 studies which performed a chemical composition analysis were reviewed. The proportions of polymers presented in this review are relative abundances (in %), which were either directly reported in the studies or derived from absolute values (e.g., counts or mass of each polymer type) when direct reports were not available. Polymers with similar chemical characteristics and fewer occurrences were categorized as a single group (see Appendix S2 for details).

2.2.4 | Potential origin of microplastics

Information on the form and chemical composition of microplastics allowed for evaluation and inference of their origin. Twenty-four of the 29 studies which reported these pieces of information were analyzed in detail. Forms or shapes of microplastics were classified into six categories: sphere (including spherule and microbead), pellet (granule), fragment (flake), fiber (filament), foam, and film (foil). The terms in parentheses were descriptions used in the reviewed studies.

3 | RESULTS

3.1 | Data quality of the reviewed primary research articles

The outcome of evaluation of data quality and reproducibility of the reviewed studies (based on the criteria defined in Section 2.2.1) are listed in Table 1 (for details, see Appendix S3). Most (83%) of the reviewed studies reported their sampling methods with adequate detail and obtained a full score. Sixty-three percent of the reviewed studies sampled a representative volume and/or mass of the matrix. Seventy percent of the studies indicated limited sample treatment and contamination in the field, prior to the laboratory analysis. Microplastics were characterized by means of spectroscopic or spectrometric methods in 27 studies. Two studies relied solely on optical methods with no additional verification of their chemical composition. Around only 20% of the investigated studies obtained full scores across the following criteria: (1) preparation of a clean environment in the laboratory prior to analysis, (2) working under clean air conditions, (3) implementing negative controls to correct for external contamination, and (4) implementing positive controls to correct for internal losses due to sample treatment processes. Finally, 37% of the reviewed studies treated the environmental samples with chemicals to remove adhesive organic matter to ensure an accurate chemical identification.

3.2 | Concentrations of microplastic particles in European rivers

3.2.1 | Microplastics in surface water samples

The concentration of microplastics in surface water samples is summarized in Figure 2. Most studies reported a similar range of microplastic concentrations (0–30 particles/m^3). Two studies reported extreme values, that is, 2072 particles/m^3 in an individual water sample collected from the Elbe River (Hildebrandt et al., 2021) and 5326 particles/m^3 from a single location along the Rhine River (Fath, 2019). Exclusion of these outliers resulted in a mean measured concentration of 608 and 145 particles/m^3, for Elbe and Rhine, respectively. A study by Mughini-Gras et al. (2021) reported extreme microplastic concentrations, that is, an average of 222,000 particles/m^3 in the Rhine (not shown in Figure 2). This value differed considerably from other reported measurements (Figure 2).

The variability in the concentration of microplastic particles are likely to depend on the sampling method, in particular, the sampling limit for the smallest particle size which can be determined with a given method. Currently, it is not possible to separate the pollution level from the influence of sampling and detection limits as there is no standardized method for sampling and determination of microplastic size.

3.2.2 | Microplastics in settled and suspended riverine sediments

The abundance of microplastic particles in the settled river sediment and suspended particulate matter is summarized in Figure 3. In the Danube River, Pojar et al. (2021) measured the lowest microplastic concentration with a mean of 100 particles/kg (min: 28 particles/kg, max: 166 particles/kg, median: 78 particles/kg). Klein et al. (2015) found low concentrations in the riverbank of the Rhine with a mean of 861 particles/kg (outlier: 3763 particles/kg, median value: 407 particles/kg). The outlier in their study was in the same range to values reported by two other studies of the Rhine River. In the Elbe River, Scherer et al. (2020) reported values ranging from the lower measurements reported for the Danube (Pojar et al., 2021) and higher measurements reported for the Rhine River (Leslie et al., 2017; Mani, Primpke, et al., 2019). The study of the Elbe River by Scherer et al. (2020) also reported an outlier equal to 16,000 microplastic particles/kg in the riverine sediment. The abundance of microplastics in the sediments of the Thames River was found to vary from 0 to 4200 particles/kg (Skalska et al., 2022, not shown in Figure 3).

3.3 | Polymer types of riverine microplastics

The proportions of polymer types in the studied rivers are shown in Figure 4. Overall, we found a very heterogenous pattern of polymer distribution across all river systems and could not identify any specific indicator types within a single river. This likely reflects the diversity of sampling methods and analytical approaches applied in different studies.

TABLE 1 Quality assessment of studies on microplastics in six European rivers.

Reference	River	Samples	Sampling methods	Representative sampling volume/mass	Sample processing and storage	Laboratory preparation	Clean air conditions	Negative control	Positive control	Sample treatment	Polymer identification	Sum
Fath (2019)	Rhine	Water	2	2	2	1	1	1	1	2	2	14
Klein et al. (2015)	Rhine	Sediment	2	2	0	0	1	0	1	2	2	10
Leslie et al. (2017)	Rhine	Sediment, suspended particulate matter	2	2	2	0	0	1	0	0	1	8
Mani and Burkhardt-Holm (2020)	Rhine	Water	2	2	2	1	1	1	0	1	2	12
Mani et al. (2015)	Rhine	Water	2	2	1	1	1	1	0	1	1	10
Mani, Blarer, et al. (2019)	Rhine	Water	2	2	1	2	1	2	2	1	2	15
Mani, Primpke, et al. (2019)	Rhine	Sediment	2	2	2	1	2	2	0	2	2	15
Mughini-Gras et al. (2021)	Rhine	Water	2	1	2	0	0	0	0	2	2	9
Schrank et al. (2022)	Rhine, Danube	Water	2	2	2	0	0	1	0	2	2	10
Urgert (2015)	Rhine	Water	2	2	2	0	0	1	0	1	2	10
van der Wal et al. (2015)	Rhine, Danube, Po	Water	2	2	2	0	1	0	0	1	1	9
Hohenblum et al. (2015)	Danube	Water	2	2	2	0	0	0	0	1	2	9
Lechner et al. (2014)	Danube	Water	1	0	1	0	0	0	0	1	0	3
Kittner et al. (2022)	Danube	Suspended particulate matter	2	2	1	1	1	1	1	1	2	12
Pojar et al. (2021)	Danube	Sediment	2	2	2	2	1	2	0	1	2	14

(Continues)

TABLE 1 (Continued)

Reference	River	Samples	Sampling methods	Representative sampling volume/mass	Sample processing and storage	Laboratory preparation	Clean air conditions	Negative control	Positive control	Sample treatment	Polymer identification	Sum
Hildebrandt et al. (2021)	Elbe	Water	2	1	1	0	0	0	2	1	2	9
Kurzweg et al. (2021)	Elbe	Sediment	1	1	0	0	0	0	1	2	2	7
Laermanns et al. (2021)	Elbe	Water, Sediment	2	2	2	0	2	1	1	2	1	13
Piehl et al. (2020)	Elbe, Po	Water	2	1	2	0	0	2	0	2	0	9
Scherer et al. (2020)	Elbe	Water, Sediment	2	2	2	0	1	2	2	2	2	15
Fiore et al. (2022)	Po	Water	1	2	2	1	1	1	0	1	2	11
Munari et al. (2021)	Po	Water	2	2	2	1	1	1	0	1	1	11
Winkler et al. (2022)	Ticino (Po)	Water, Sediment	2	2	2	2	2	2	2	2	2	18
Devereux et al. (2022)	Thames	Water	2	0	1	1	1	1	0	0	2	8
Horton et al. (2017)	Thames	Sediment	2	0	2	0	1	2	0	1	2	10
Rowley et al. (2020)	Thames	Water	2	2	2	1	2	1	0	2	1	13
Kaliszewicz et al. (2020)	Vistula	Water	1	0	2	1	1	1	0	1	1	8
Rytelewska and Dąbrowska (2022)	Vistula	Sediment	1	1	0	0	0	0	0	1	2	5
Sekudewicz et al. (2021)	Vistula	Water	2	0	2	2	1	1	0	1	2	11
Sekudewicz et al. (2021)	Vistula	Sediment	2	1	2	2	1	1	0	0	2	11

TABLE 1 (Continued)

Reference	River	Samples	Sampling methods	Representative sampling volume/mass	Sample processing and storage	Laboratory preparation	Clean air conditions	Negative control	Positive control	Sample treatment	Polymer identification	Sum
Average score			1.83	1.47	1.60	0.67	0.80	0.93	0.43	1.27	1.63	10.63
Percentage of studies that scored 2			83%	63%	70%	17%	13%	23%	13%	37%	70%	
Percentage of studies that scored 1			17%	20%	20%	33%	53%	47%	17%	53%	23%	
Percentage of studies that scored 0			0%	17%	10%	50%	33%	27%	70%	10%	7%	

Note: The scores indicate the reproducibility and the reliability of the data and the experimental design of the investigated studies. The highest possible score for each criterion is “2”, representing highest reproducibility. A score of “1” denotes limited reproducibility of the data and experimental design. A score of “0” denotes the lowest degree of reproducibility. The assessment was performed based on the protocol developed by Koelmans et al. (2019) (see Appendix S3 for details).

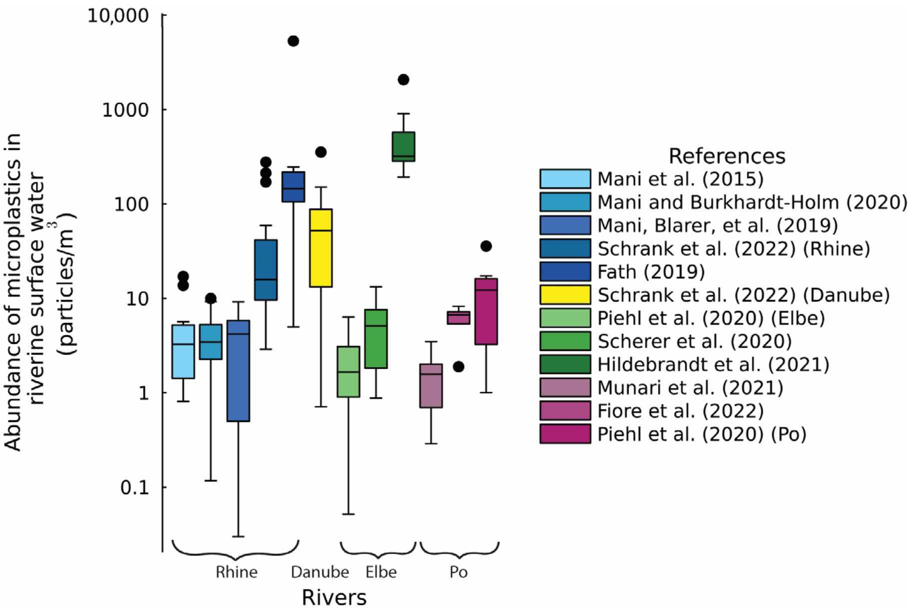

FIGURE 2 Microplastics concentrations in the water phase (particles/m^3) of the reviewed rivers in log-scale.

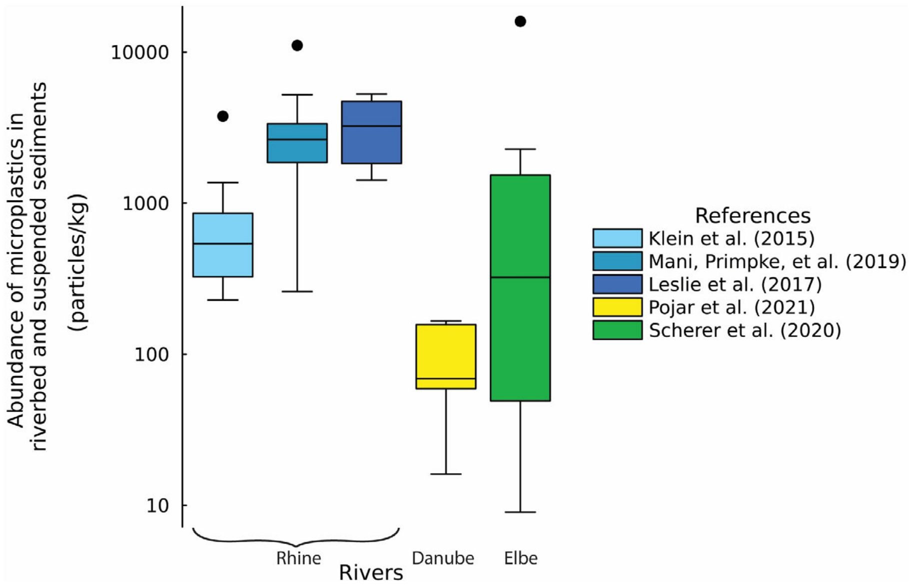

FIGURE 3 Microplastics abundance in sediment (particles/kg dry mass) in selected European rivers.

However, we found polystyrene (PS), polypropylene (PP), and polyethylene (PE) to be the most abundant polymers. In most studies of the Rhine River, PS, PP, and PE accounted for 70%–80% of all pollutants (Figure 4). In contrast to these findings, Mughini-Gras et al. (2021) reported polyamides (PA; 30%) and polyvinyl chlorides (PVC; 26%) as the most abundant polymers in the surface water of the Rhine River with PP, PE, and PS accounting for only 8% of the microplastics. In sediment samples collected from the Rhine River, acrylates accounted for 70% and the quantities of low-density microplastics (PS, PP, PE; 29% combined) were low (Mani, Blarer, et al., 2019). In addition, Mani, Blarer, et al. (2019) indicated 68% of all particles found in the filtered surface water samples to be PS divinylbenzene (PS-DVB) with no presence of PE or PP. In studies of the Danube River, the cumulative share of PE, PS, and PP was comparable to that reported for the Rhine River. Scherer et al. (2020) found the polymer distribution in the sediments to be more diverse than the distribution in the water column. In the water phase, more than 90% of microplastics were classified as PS, PP, and PE (value for the sediment: 65%) (Scherer et al., 2020). Kurzweg et al. (2021) reported high abundance of PE (33%),

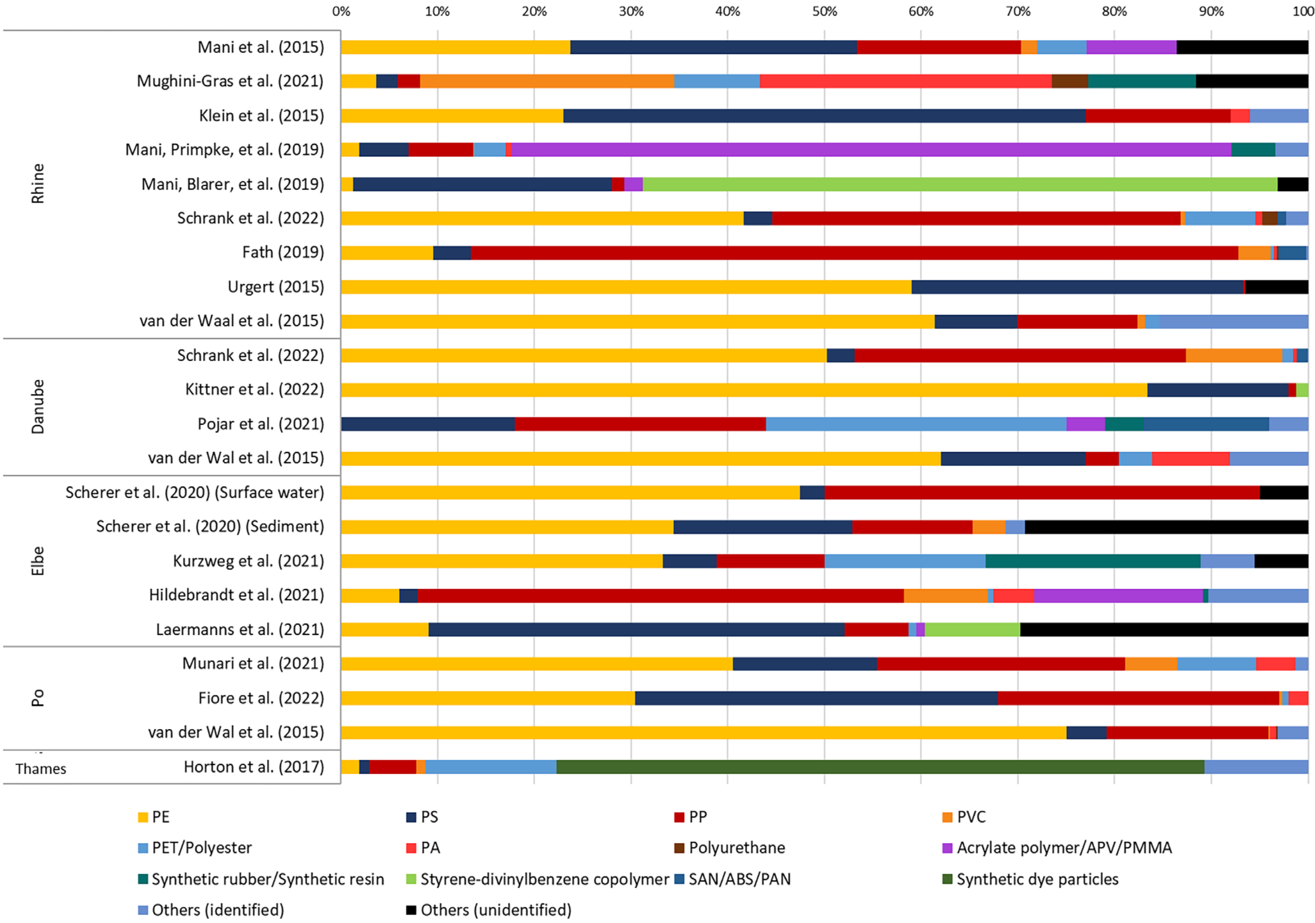

FIGURE 4 Representation of the proportions (in %) of polymer types of the microplastic particles found in the reviewed studies.

synthetic resins (22%), and polyethylene terephthalate (PET; 17%) with lower quantities of PP (11%) and PS (6%) in the sediments of the Elbe River. Hildebrandt et al. (2021) studied surface water of the Elbe River and reported 50% of the polymers to consist of PP with acrylates as the second most abundant (17%) among the identified polymer types. In the Po River, the proportion of PE, PS, and PP was also high (over 80%) (Munari et al., 2021; van der Wal et al., 2015). For the Thames River, a high proportion (67%) of synthetic dye particles was found in the sediments (Horton et al., 2017). The analysis for the composition of microplastics in the Vistula River was not available.

3.4 | Evaluation of the origin of microplastics

A summary of the potential sources of microplastic debris found in the reviewed studies is presented in Table 2. A total of five origins of primary microplastics and six origins of secondary microplastics was identified. These findings provide an indication of a widespread problem and a high diversity of sources of riverine microplastics. Primary microplastics (pellets and spheres) arise from industrial sectors, pharmaceuticals, and personal care products (PPCPs) (Klein et al., 2015; Mani et al., 2015; van der Wal et al., 2015). Primary spherical microplastics consisting of PS (applied as abrasive agents) and ion exchange resins were predominantly found in the Rhine River (Mani, Blarer, et al., 2019). Primary spherical microplastics consisting of PE (used in cosmetic products for skin exfoliation) were found across multiple locations along the Rhine River (Klein et al., 2015; van der Wal et al., 2015). Other primary microplastics (pellets and spheres) were likely to consist of raw materials for industrial mass production (Urgert, 2015; van der Wal et al., 2015). These were found in the Rhine, the Danube, and the Po Rivers. No explicit industrial sources of microplastic pollution were identified for the Thames River and the Vistula River despite strong industrial presence in the region.

TABLE 2 Overview of different microplastic sources, forms, and types from the reviewed studies.

estimated origin	River	Common forms (and the original form description provided in each study)	Common polymer types	Studies
Industry: abrasive (e.g., for compressed air blasting)	Rhine	Spheres (spherules)	PS	Mani et al. (2015)
	Rhine, Danube, Po	Spheres (microbeads)	PE	van der Wal et al. (2015)
Industry: ion exchange resins (for water softening and for various industrial wastewater purification processes)	Rhine	Spheres (spherules)	PS	Mani and Burkhardt-Holm (2020)
		Spheres (microbeads)	Polystyrene-divinylbenzene, PS	Mani, Blarer, et al. (2019)
		Spheres (beads)	PS	Schrank et al. (2022)
	Elbe	Spheres	Polystyrene-divinylbenzene, PS	Laermanns et al. (2021), Scherer et al. (2020)
Industry: preproduction of industrial raw materials	Rhine	Pellets	Ethylene propylene diene monomer rubber	Klein et al. (2015)
		Spheres (spherules)	PMMA, PS	Mani et al. (2015)
		Spheres (spherules)	Expanded polystyrene	Urgert (2015)
	Rhine, Danube, Po	Pellets	PS	van der Wal et al. (2015)
	Danube	Pellets, spheres (spherules)	Not specified	Lechner et al. (2014)
Industry: unspecified diverse sectors	Rhine	Spheres (spherules)	PS	Urgert (2015)
	Danube	Pellets	Not specified	Hohenblum et al. (2015)
	Po	Pellets	PE, PP	Fiore et al. (2022)
		Pellets	Not specified	Munari et al. (2021)
Pharmaceuticals and personal care products (PPCP)	Rhine	Spheres (spherules)	PS	Klein et al. (2015)
		Spheres (spherules)	PE	Mani and Burkhardt-Holm (2020)
		Spheres (spherules)	PE	Mani et al. (2015)
		In various forms (shredded scrubs)	PE	Urgert (2015)
	Rhine, Danube, Po	Spheres (microbeads)	PE	van der Wal et al. (2015)
Synthetic textiles (for clothing, shopping bags and packaging sacks)	Rhine	Fibers	PA	Fath (2019)
		Fibers	Not specified	Klein et al. (2015)
		Fibers, films	PP, PE, PS	Mani and Burkhardt-Holm (2020)
		Fibers	PET/polyester	Schrank et al. (2022)
	Danube	Fibers	Not specified	Pojar et al. (2021)
	Elbe	Fibers	PE, PET	Kurzweg et al. (2021)
	Po	Fibers (filaments)	PA	Fiore et al. (2022)
		Fibers	PA	Munari et al. (2021)
	Thames	Fibers	PP, PS	Horton et al. (2017)
Fragmentation from diverse and	Rhine	Fragments	PE, PP	Klein et al. (2015)
		Spheres, fibers	Not specified	Leslie et al. (2017)
		Foams	PE, PS	

TABLE 2 (Continued)

estimated origin	River	Common forms (and the original form description provided in each study)	Common polymer types	Studies
unidentifiable large plastic pieces				Mani and Burkhardt-Holm (2020)
		Fibers	PP	Mani et al. (2015)
		Fragments	PE, PP	Schrank et al. (2022)
		Films	PE	Urgert (2015)
	Rhine, Danube, Po	Foams	Expanded polystyrene, polyurethane	van der Wal et al. (2015)
	Danube	Not specified	PE, PP, PS	Kittner et al. (2022)
	Elbe	Fragments, films (foils)	PE, PP	Kurzweg et al. (2021)
		In various forms	PE, PP	Scherer et al. (2020)
	Po	Foams	Expanded polystyrene	Fiore et al. (2022)
		Pellets (granules)	PP	Fiore et al. (2022)
		Fragments	PE, PP	Munari et al. (2021)
	Thames	Fragments, films	PE, PP	Rowley et al. (2020)
	Vistula	Fragments, films (foils)	PE, PP	Rytelewska and Dąbrowska (2022)
		Fibers	PS, PP	Sekudewicz et al. (2021)
Antifouling ship paint and varnishes	Rhine	Fragments	Acrylates/polyurethanes/ varnish	Mani, Primpke, et al. (2019)
	Elbe	Not specified	Synthetic resins	Kurzweg et al. (2021)
Thermoplastic road surface marking paints	Thames	Fragments	Synthetic dyes	Horton et al. (2017)
Tire wear (urban areas, traffic)	Danube	Not specified	Styrene butadiene rubber	Kittner et al. (2022)
	Thames	Not specified	Styrene butadiene rubber	Devereux et al. (2022)
Incomplete and unprofessional incineration of plastics	Rhine	Fragments	PE	Fath (2019)

Abbreviations: PA, polyamide; PE, polyethylene; PET, polyethylene terephthalate; PMMA, polymethyl methacrylate; PP, polypropylene; PS, polystyrene.

Secondary microplastics have diverse origins and their forms and chemical composition exhibit a wider spectrum in comparison to primary microplastics. Fibers were identified in all rivers except for the Vistula River. Synthetic textiles from clothes, shopping bags, and packaging sacks were potential sources of those fibers. Styrene butadiene rubber fragments found in the Danube and the Thames Rivers were identified as tire wear particles (Devereux et al., 2022; Kittner et al., 2022). Fragments consisting of synthetic dyes and resins were identified as antifouling ship paints and road surface marking paints.

4 | DISCUSSION

4.1 | Data quality assessment of the reviewed studies

Our quantitative assessment provided insight into how reproducible, representative, and reliable the available empirical research was. Studies that did not report experimental procedures with sufficient details, as per recommendations by

Koelmans et al. (2019), obtained lower scores in the quality assessment. However, it was not possible to determine whether these details were unintentionally or deliberately omitted by the authors. Consequently, it was not possible to ascertain whether a lack of detail in described research equated to not following best-practice experimental protocols. This constitutes a limitation of our assessment. However, we successfully identified one of the main factors resulting in low comparability among empirical studies, that is, lack of positive controls. Seventy percent of the reviewed studies did not provide a positive control and obtained a score of zero in the quality assessment (Table 1). The standard operating procedure for separation and enrichment of microplastics consists of (1) sample volume reduction via filtration or sieving, (2) density separation, and (3) destruction of natural debris with chemicals and/or enzymes (Klein et al., 2018). During sample pretreatment, microplastic particles might be lost before the final measurement and identification (Koelmans et al., 2019), causing an underestimation of the quantity of microplastics (Weber & Kerpen, 2022). Hence, it is essential to provide a representative positive control with replicates ($n \geq 3$), to validate the procedure for sample processing. This is particularly relevant in situations when it is necessary to correct for underestimation of microplastics due to low but reproducible recovery rates (Hermsen et al., 2018; Koelmans et al., 2019). In addition to the positive controls, which are designed to minimize influence of internal loss during sample pretreatment, further precautions should be taken to eliminate contamination from external sources (Noonan et al., 2023). Contamination can consist of airborne synthetic components so it is crucial to keep the samples sealed or covered whenever possible both in the field (over the course of sampling and transport) and in the laboratory (during the analysis) (Vandermeersch et al., 2015; Wesch et al., 2016). Working in a clean laboratory environment, under laminar flow cabinets, and wearing cotton lab coats during analysis constitute necessary working standards (Hermsen et al., 2018; Rowley et al., 2020). However, these measures were not taken in multiple reviewed studies (Table 1) as 17% and 13% of the studies fulfilled all requirements in the criteria "laboratory preparation" and "clean air condition," respectively. Instead, negative controls were employed (in 21 out of 29 studies) to compensate for potential impacts of external contamination.

Low-quality scores of many of the reviewed studies highlighted the need for development of comprehensive standard operating procedures to ensure better data quality and higher comparability. Guidelines set out by Koelmans et al. (2019) and Cowger et al. (2020) can be regarded as initiatives of high reference value and should be considered in future studies.

4.2 | Abundance of microplastic particles in rivers

Our review demonstrated that microplastics were ubiquitously present in major European rivers, regardless of whether the sediment or the water phase was sampled and whether headwaters or tailwaters were studied. The abundance of microplastics in surface water samples has stronger variations than that in suspended and riverbed sediment samples, which are less dependent on various hydrological conditions of the river (Talbot & Chang, 2022). Microplastic loads beyond the water surface and the riverbed sections remain mostly unknown, possibly resulting in biased estimates of actual loads when only part of the water column was sampled and analyzed (Fath, 2019; Santillo et al., 2019). Microplastics depth profiles of rivers suggest that microplastics are transported at different levels of the water column, which is not consistent to the theoretical model mainly linked to microplastics density, that a large portion of microplastics is either floating on the surface or deposited to the bottom in rivers (Al-Zawaidah et al., 2022; Lenaker et al., 2019). We emphasize the need to improve comparability of quantitative measurements of field samples. To ensure representative sampling, multiple samples should be collected along the depth of the water column. Organic and inorganic matter presents another factor that influences the measured results. It accumulated in nets or sieves used to sample the water (Schrank et al., 2022) and as a result, particles with dimensions even smaller than the mesh sizes were also trapped and retained because they could not pass through the clogged meshes (Urgert, 2015; van der Wal et al., 2015). Since the presence of particulate matter is different for each individual sample, measurements of microplastic concentration in the water column do not necessarily demonstrate the actual abundance of the particles within the size range of interest, even when the sampling is carried out with an identical setup. This suggests that for analyzing microplastics from filtered samples with rich particulate and fibrous matter that might cause entrapment of microplastics of dimensions smaller than the mesh size of the sampling apparatus, microplastics should be filtered again to characterize their actual size fractions. We identified two other major issues which could affect comparability among studies: (1) different filter materials were used (e.g., plastics, stainless steel) and (2) filter mesh sizes ranged from 20 μm (Kaliszewicz et al., 2020) to 500 μm (Lechner et al., 2014), including non-standard apparatus (Laermanns et al., 2021; Mughini-Gras et al., 2021). We strongly recommend publishing microplastic concentrations together with details of the experimental apparatus and the investigated size ranges. In addition, the orientation of the fibers passing through the cross-section area of a sampling equipment also influences the quantification outcome, as fibers have totally different dimensions (lengthwise and crosswise). Thus, the microplastics can pass or be intercepted (Liebmann et al., 2015). Finally, the analytical methods were found to differ among the reviewed studies. Some studies performed particle counting visually with a microscope (Hohenblum et al., 2015; Lechner et al., 2014), which is less accurate than chemical analytical approaches including the Fourier-transform infrared spectroscopy (applied in 19 studies) or the Raman spectroscopy (applied in 5 studies). The outlined differences in research methods complicate quantitative comparisons of the results.

Based on the evidence from field observations, the debate about whether the concentration of microplastics in the river increases over the river's course remains unresolved in contrast to the well-documented pharmaceutical concentrations that rise along the river's course (Fath, 2019). Microplastic concentrations were found to be significantly correlated with population density in Japan (Kataoka et al., 2019), whereas no significant correlation between the two variables was observed in a study involving the Rhine River (Klein et al., 2015). The latter might be attributed to variable microplastic concentrations arising from changing hydrodynamic conditions of the investigated stretch of the river. Talbot and Chang (2022) carried out a review of empirical studies on the topic but reached indeterminate conclusions. A possible explanation for inconclusive evidence is that the population density might not necessarily have a positive correlation with the intensity of anthropogenic activities, as point sources like industrial wastewater and municipal sewage effluents notably increase the amount of microplastics in the local environment (Estahbanati & Fahrenfeld, 2016; Klein et al., 2015; Leslie et al., 2017). The retention of microplastics along the river is also a common process. Microplastics at the upstream might not reach the downstream and the particles might be contained or deposited in impounded sections of the river (Pojar et al., 2021), for example, near weirs in rivers (Mani et al., 2015). In addition, environmental factors such as high discharge events and floods, flow velocity, currents, and turbulences might also have an impact on the empirical outcomes when the amount of data is scarce (Fath, 2019), further impeding comparisons between studies.

4.3 | Polymer types of riverine microplastics

We found that PS, PP, and PE were the most frequently identified microplastics. This is likely due to a high availability of plastic products containing these polymer types, as it was suggested that commonly used plastic products are at an increased risk of improper disposal through littering into the environment (Schrank et al., 2022). According to PlasticsEurope (2019), these three plastic types account for more than half (56.1%) of Europe's demand for plastic (PE: 30.3%, PP: 19.7%, and PS: 6.1%), whereas the demand for other types of plastics (PVC: 9.6%, PET: 8.4%, polyurethane: 7.8%) is much lower. The density of microplastics also has an impact on their occurrence and abundance in the water column (Liu et al., 2020; Rowley et al., 2020). Plastics with a low density generally have a higher buoyancy and will be transported more easily (Fath, 2019; Klein et al., 2015), whereas particles with a higher density are comparatively less mobile and thus more likely to settle (Besseling et al., 2017; Pojar et al., 2021). As the surface water was sampled in most of the reviewed studies, types of plastics with a higher density than PE, PP, and PS may not have been adequately represented because of the limitations of this sampling approach. The polymer types PS, PE, and PP were also found in the sediment samples (Klein et al., 2015; Kurzweg et al., 2021; Scherer et al., 2020). Scherer et al. (2020) suggested that density was affected by biofouling (i.e., the formation of biofilms by accumulation of microorganisms) and confirmed that sinking could occur due to the formation of a biofilm on the particles (Kaiser et al., 2017; Scherer et al., 2020). In addition, additives such as metals, stabilizers, or pigments that are often added to plastic products increase the specific density of microplastics, resulting in faster sinking (Turner & Filella, 2021). Furthermore, the surface morphology (Burrows et al., 2020) and size (Ma et al., 2019) of microplastics can impact the adsorption of pollutants and affect their settlement across the water column (Fath, 2019).

In addition to PE, PP, and PS, other polymer types such as acrylates/PURs/varnishes (APV) (Mani, Primpke, et al., 2019), PET/polyester and synthetic resins (Kurzweg et al., 2021) were found in the sediment, indicating the polymer composition of the sediment to be more diverse than that of the surface water. However, identification of microplastics in the sediment was shown to be difficult (Laermanns et al., 2021; Scherer et al., 2020) with a high proportion (30%) of particles whose polymer type could not be determined. Laermanns et al. (2021) argued that the high percentage of unidentifiable microplastics reflected the limitations of their polymer determination method (pyr-GC-MS) which showed better results for determination of PS, PP, and PE. This indicated that the selected method for polymer determination can impact the assessment of polymer composition (Primpke et al., 2020). Leslie et al. (2017) suggested that with the large number of plastic types occurring today, it is a major challenge to investigate their diversity with a single analytical method. Furthermore, in many studies only a subsample of all microplastic debris was analyzed with the outcome extrapolated to the total number of microplastic types. This carries a risk of erroneous estimates of the proportion of individual types of plastics that are present in the whole sample and might lead to biased results (Schrank et al., 2022). Hence, the total number of particles identified by means of laboratory methods becomes important because the more particles are examined, the more statistically significant are the polymer determinations (Fath, 2019; Koelmans et al., 2019).

4.4 | Origin of riverine microplastics

Overall, the origins of microplastics could not be determined with high certainty or accuracy (Mani, Blarer, et al., 2019; Urgert, 2015) and much of the original purpose of the microplastics could not be determined, especially in regard to secondary microplastics (Liebmann et al., 2015). Consequently, their origins were reported as unknown (Scherer et al., 2020). Due to their characteristic and uniform appearance, the origin of primary microplastic particles is easier to determine in contrast to the more fragmented secondary particles. The surface of secondary microplastics is usually strongly abraded and weathered, which alters their chemical composition, affecting the infrared and Raman spectra (Dong et al., 2020; Fernández-González et al., 2021). This results in difficulties in accurate identification and subsequent evaluation of the sources of the investigated particles. Furthermore, the evaluation of the origins of microplastics is often limited by the applied analytical method. Studies that applied spectroscopic analytical methods had difficulties in characterizing black as well as thin colorless objects (Leslie et al., 2017). In contrast, studies which used destructive chemical characterization methods (e.g., thermal extraction desorption-gas chromatography/mass spectrometry) were not able to provide any information on the texture and the shape of particles, if bulk samples were used directly for chemical analysis with no prior visual assessment.

Overall, we showed (Table 2) that various industrial sectors are responsible for the input of primary microplastics into rivers. Cosmetic products (denoted as PPCPs in Table 2) introduce other primary microplastics. There are ongoing public discussions on restricting the use of primary microplastics in cosmetic products as these pollute the aquatic ecosystems. However, there is no EU-wide ban on microplastic use in cosmetics at present. Some EU countries have introduced restrictions but these only apply to products that get washed off with water after use. As a result, the emission of primary microplastics from cosmetics will not be eliminated rapidly (Anagnosti et al., 2021; Bertling et al., 2018).

There are various origins of secondary microplastic debris. Synthetic fibers, fragments of larger plastic items and abraded particles from plastic-containing materials make up most of the secondary microplastics in European rivers (Table 2). Over 90% of the microplastics found in the Thames River by Rowley et al. (2020) were films and fragments. The authors assumed that these microplastics originated from the fragmentation of plastic packages, since those packages consist mostly of PE and PP, which were also identified as the most abundant. Textile and clothing fibers are released into the environment through the washing process by private households and the industry. The fibers proceed to enter the surface waters through wastewater discharge from sewage treatment plants and through the spreading of the sewage sludge. Browne et al. (2007) reported a release of over 1900 fibers after a single washing cycle of a polyester garment. Furthermore, fishing equipment is considered another major source of microplastic fibers (PA, Wagner et al., 2014; polyester, Morgana et al., 2018) and was reported to contribute 18% of the plastic waste in the marine environment (Andrady, 2011). It is likely that this source of microplastics is not included in the reviewed studies because river fishing is less common than open sea fishing. Only two of the reviewed studies identified tire abrasion (styrene butadiene rubber particles; Devereux et al., 2022; Kittner et al., 2022), one of the largest contributor of microplastic pollution in terrestrial ecosystems (Bertling et al., 2022; Boucher & Friot, 2017), as a source of riverine microplastics. This might be explained by the fact that tire wear microplastics are being deposited at roadsides (within several meters of where they were formed) with relatively few microplastics entering flowing waters (Gehrke et al., 2021; Hagström, 2021).

Direct atmospheric deposition and airborne spreading of microplastics into rivers is also possible (Fath, 2019; van der Wal et al., 2015). Microplastic particles were found in Lake Toma (270 particles/m^3), near the source of the Rhine River (Fath, 2019) at an elevation of over 2300 m despite a lack of industry, agriculture, or settlement in the immediate vicinity. The author speculated that the particles constituted plastics which were incompletely incinerated, moved via aerosol transport and deposited via precipitation and snowmelt (Fath, 2019), causing microplastics to become emerging pollutants in high altitude remote areas (Allen et al., 2019; Feng et al., 2021). Transport of microplastics through air was also observed near the waterways of the Thames River after firework displays (Devereux et al., 2022), suggesting that the airborne transport of microplastics is of high environmental relevance and requires further scientific investigations.

5 | FUTURE PERSPECTIVES

To promote further understanding of the fate of microplastics and to mitigate microplastic pollution in riverine environments, we summarize the current state of knowledge, scientific challenges, and potential future pathways for action.

5.1 | Current challenges and future steps

We urgently need comprehensive and comparable data obtained through high-resolution monitoring networks that analyze representative samples, following accepted protocols.

Monitoring comparability: Currently, there are no standard research methods for assessing the concentrations of microplastics. Despite efforts to standardize protocols for the analysis of environmental microplastics, many laboratories rely on in-house and not externally validated methods. This undermines the comparability of results obtained in different laboratories (Bank et al., 2022). Furthermore, many studies analyze different and inconsistent sets of sample characteristics (e.g., size distribution, debris shape, color, chemical composition, etc.) and provide measurements that are often not comparable (e.g., from different river depths). Comparable data are necessary to inform decision-making with a goal to develop strategies to reduce microplastic pollution (Dris et al., 2015). Thus, joint efforts are urgently needed to enable the standardization of sampling and analytical procedures and to develop monitoring and reporting standards (Cowger et al., 2020).

Monitoring continuity: Many studies provide information on microplastics in rivers as snapshots in time. This often results in high uncertainties in regard to microplastic pollution at longer temporal scales (Munari et al., 2021). To improve the understanding of factors that impact the presence of microplastics (Devereux et al., 2022), continuous monitoring of plastic debris in rivers over longer timeframes should be encouraged (Schrank et al., 2022; van der Wal et al., 2015) as it would better reflect the effects of dynamic natural processes and anthropogenic activities (Hohenblum et al., 2015; Santillo et al., 2019).

Monitoring representativity: As the spatial scale increases, the heterogeneity and uncertainty of on-going processes at different locations increase as well (Schulp & Alkemade, 2011; Verburg et al., 2013). Individual studies select different field scales for sample collection and analysis, which may affect the conclusions regarding microplastic sources and sinks (Talbot & Chang, 2022). Thus, researchers investigating microplastics should select a representative spatial scale for their studies, analogous to the representative elementary volume (Bachmat & Bear, 1987; Oda, 1988). A representative spatial scale should be large enough to minimize inhomogeneity and small enough to reduce heterogeneity. Studies that analyze samples collected from a limited number of sites along stretches of long rivers ought to be regarded as exploratory because observations obtained at such large spatial scales are affected by multiple factors and are case-specific. In the future, the study of tributaries should be prioritized because tributaries can contribute significant amounts of microplastics to the rivers (Kittner et al., 2022; Klein et al., 2015; Laermanns et al., 2021). In addition, tributaries have sufficient size and complexity to carry out detailed empirical studies, develop models and test hypotheses (Barrows et al., 2018).

Monitoring comprehensivity: Environmental change is a result of complex interactions between natural and anthropogenic processes which occur across different spatiotemporal scales. Understanding and quantifying environmental change must be based on comprehensive data that capture the complexity of the Earth systems (Bouwer et al., 2022). Currently, the presence of microplastics in riverine surface water, sediments, and organisms is investigated separately. Data describing different components of the environment are not yet integrated into existing hydrological or ecological models. Comprehensive monitoring of microplastics in rivers requires a broad assessment of all relevant matrices. Thus, the results of different studies which involve multiple environmental components, including fauna and flora, should be collected and brought forward to enable better integration of the available data. Considering that data-driven analysis can characterize patterns in systems with complex intrinsic nature (Bouwer et al., 2022), the use of integrated data on microplastics might compensate for the limitations of deriving conclusions from isolated studies (van Emmerik & Schwarz, 2020). Furthermore, well-designed databases will facilitate data collection and transferability.

5.2 | Beyond scientific research

As the global production and consumption of plastics is continuously increasing (Chen et al., 2021), more plastic debris, including microplastics, has been released into the environment. For example, due to the COVID-19 pandemic, the

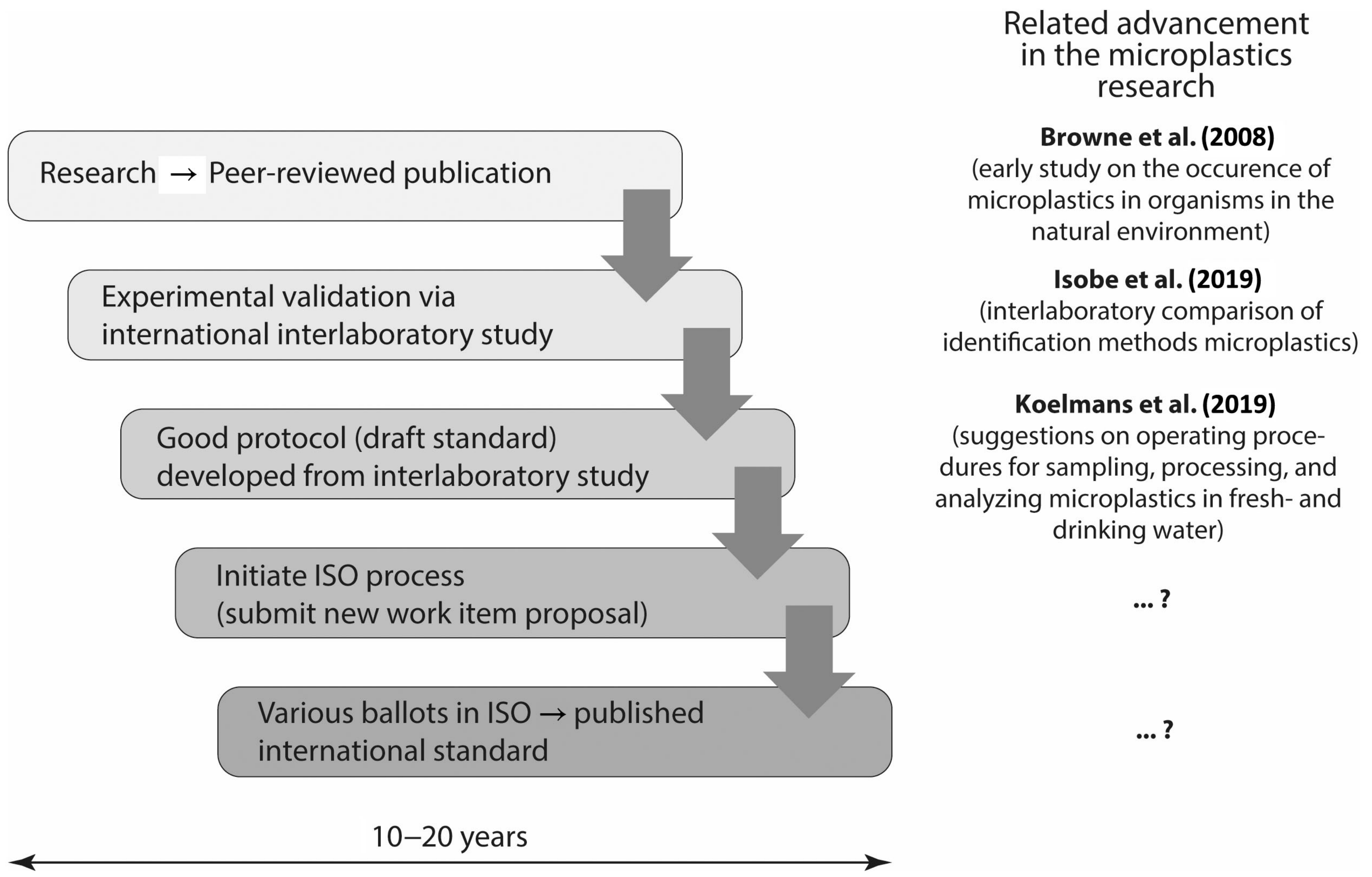

FIGURE 5 Five steps needed to develop a standard of measurement and characterization (left, edited based on Clifford et al., 2020) and essential advancements in microplastics research (right).

amount of biomedical waste, a large part of which consisted of plastics, increased significantly (Benson et al., 2021; Peng et al., 2021) and was subsequently found in open environment (Shen et al., 2021). Over the years, reports of the harmful effects of plastic debris on living organisms (Kögel et al., 2020; Marczynski & Lieleg, 2021) and their widespread presence in the environment (Su et al., 2022) have influenced policymakers to implement specific regulations relevant to the production and use of plastic products (e.g., Regulation EC No 1907/2006). Studies which carried out extensive monitoring at the same locations were shown to be an effective tool for identifying the entry points for specific microplastic types (Mani, Blarer, et al., 2019). Such monitoring schemes should be carried out by the government and environmental protection organizations to formulate better surveillance and regulation systems for the industry. The precautionary principle with focus on prevention measures is currently the most effective strategy to reduce inputs of plastics and microplastics into the aquatic environment (Fath, 2019; van der Wal et al., 2015; Whitehead et al., 2021). The precautionary principle is preferable over the more expensive and impractical remedial measures, since plastic contaminants cannot be efficiently or economically removed from the environment (Hidalgo-Ruz et al., 2012; Ivar do Sul & Costa, 2014; Santillo et al., 2019; Whitehead et al., 2021).

6 | CONCLUSIONS

Microplastics were identified in almost all individual samples in the reviewed studies of six European rivers. The concentrations of riverine microplastics differed by several orders of magnitude. The concentration of microplastics was found to be the highest in surface waters of the Rhine and Elbe Rivers, whereas the highest concentration of microplastics in the sediments was found in the Elbe River. The quantitative measurements of sediment samples were shown to have a lower variation in comparison to the surface water samples. The majority of primary microplastic particles were pellets and spheres which originated from industrial raw materials, mass production, and cosmetic products. Secondary microplastics were formed during the fragmentation of diverse large plastic pieces and their original purpose was not easily discriminated. The most frequently identified polymer types in the water phase were PE, PP, and PS likely due to their low density and their frequent as well as widespread use in Europe. A wider variety of polymers consisting not only of polymer types with higher densities such as PET and PVC, but also of lighter polymers that underwent biofouling and hetero-aggregation in the environment, were found in the sediments and the suspended particulate matter. A comparison of measurements of microplastics was hampered by the scarce data available and a lack of standardized research concepts and methods. Additional investigations focusing on riverine microplastics in major rivers and their tributaries are needed. Similarly, more quantitative data on the abundance and distribution of microplastics, form or shape categories, and polymer types should be collected through comparable experimental methods. Standardization of methods as well as development of uniform definitions and units are necessary to compare research outcomes. Furthermore, reporting details of the experimental design (sampling, processing, analysis) and providing documentations describing the methods are crucial. Finally, issues with comparability among studies and the associated uncertainties can be overcome by implementing international standards, development of which ought to be prioritized by the scientific community (Steps 4 and 5 in Figure 5).

AUTHOR CONTRIBUTIONS

Sijia Gao: Formal analysis (lead); investigation (lead); visualization (equal); writing—original draft (lead); writing—review and editing (equal). **Natalie Orlowski:** Formal analysis (supporting); supervision (equal); writing—original draft (supporting); writing – review and editing (equal). **Franziska Kristin Bopf:** Formal analysis (lead); investigation (lead); visualization (equal); writing—original draft (lead); writing—review and editing (supporting). **Lutz Breuer:** Conceptualization (lead); formal analysis (supporting); supervision (equal); visualization (supporting); writing—original draft (supporting); writing—review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known conflict of interest that could have appeared to influence the work reported in this review.

OPEN RESEARCH BADGES

This article has earned an Open Data badge for making publicly available the digitally shareable data necessary to reproduce the reported results. The data are available at 10.17605/OSF.IO/Z68UW.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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