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Microplastics and Nanoplastics

METHODOLOGY

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Toward harmonised monitoring of plastic pollution: description of a systematic review to evaluate and apply reproducible methods

Stefano Aliani[1*], Amy Lusher[2†], Giuseppe Suaria[1†], Sebastian Primpke[3], Lisa Roscher[3], Bavo De Witte[4], David Vanavermaete[4], Katrien Verlé[4], Vladimir Nikiforov[5], Dorte Herzke[5], Andrea Paluselli[1], Vincenzo Donnarumma[1], Jakob Strand[6], Vitor Hugo da Silva[6], Francois Galgani[7], Gabrielle Hairabedian[2] and Bert Van Bavel[2]

Abstract

Plastic pollution monitoring programs use a wide array of methods, protocols, and analytical approaches, making it difficult for researchers and practitioners to determine which techniques to apply, where, and how. This lack of harmonisation across environmental compartments and plastic size classes has led to inconsistent data and limited comparability across studies. To address this, a systematic review of monitoring methods from 1960 to 2021 was conducted, encompassing both peer-reviewed and grey literature. Techniques were categorised into Reproducible Analytical Pipelines (RAPs), each comprising six core steps: survey design, sample collection, sample preparation, analytical detection, quantification, and data reporting. Each RAP was assessed using Technological Readiness Levels (TRLs) to evaluate maturity and suitability for standardised monitoring. The review revealed that while robust and repeatable methods exist, they are inconsistently applied. At the time of this review, atmospheric plastics was underrepresented, highlighting a critical gap in monitoring efforts. The findings underscore the urgent need for a global, objective framework to guide the selection and implementation of plastic pollution monitoring methodologies. This paper lays the foundation for such a framework by presenting a methodology to identify mature, reproducible methods and prioritise areas for further development. Future work should focus on harmonising protocols across compartments and size classes, improving transparency in data reporting, and building consensus around standardised practices to enable global comparability and policy relevance.

Keywords Litter, Monitoring method, Macroplastics, Mesoplastics, Microplastics, Nanoplastics, TRL

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†Amy Lusher and Giuseppe Suaria contributed equally to this work.

*Correspondence:
Stefano Aliani
stefano.aliani@ismar.cnr.it
[1]Istituto di Scienze Marine, CNR-ISMAR, Forte S.Teresa, Lerici 19032, Italy
[2]NIVA, Økernveien 94, Oslo 0579, Norway
[3]Biologische Anstalt Helgoland, Shelf Sea Systems Ecology, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Reseach, Kurpromenade 201, 27498 Helgoland, Germany
[4]Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), ILVO Marine, Jacobsenstraat, 1, Oostende 8400, Belgium
[5]NILU, Hjalmar Johansens Gate 14 Fram Centre, Tromsø, Norway
[6]Department of Ecoscience, Aarhus University, Frederiksborgvej 399 4000, Roskilde, Denmark
[7]IFREMER, Brest, France

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Introduction

Quantifying the extent of plastic pollution in the environment remains a critical and unresolved challenge. Despite more than two decades of research [1, 2], the harmonisation of monitoring approaches across environmental compartments and plastic size classes has yet to be achieved. An overwhelming diversity of methods and protocols has been developed, following a plethora of different approaches driven by diverse scientific needs and technical capabilities. However, as for any environmental assessment, robust monitoring methods based on harmonised, reproducible protocols selected through objective and clearly defined criteria, are critically needed, and many attempts in this direction have been carried out [3–9]. This includes developing guidelines tailored to specific plastic sizes and environmental matrices, often based on the collective expertise and selective knowledge of expert groups [10–13].

Guidelines have been effective for compartments and size classes for which the procedures are well established, and many regulatory bodies and stakeholders endorsed their application, benefiting from their reproducibility. For instance, among many reports, there are detailed methodological descriptions for birds [14], water and sediments [15], as well as a comprehensive review of methods provided by the Ministry of Environment of Japan [16]. They have been less effective when procedures were not well established or regulating bodies did not converge on comparable methods. Many expert groups (e.g., Arctic Monitoring and Assessment Programme, AMAP; Group of Experts on the Scientific Aspects of Marine Environmental Protection, GESAMP; The Convention for the Protection of the Marine Environment of the North-East Atlantic, OSPAR; Technical Group on Marine Litter, The Convention on the Protection of the Marine Environment of the Baltic Sea Area (HELCOM), EU-MSFD TGML, etc.) are still actively working on the topic, with their recommendations increasingly integrated into international monitoring frameworks [11]. A fundamental challenge lies in improving existing guidelines, making them more adaptable, avoiding abrupt changes that could undermine functioning monitoring systems, also considering the fragmented nature of plastic governance across national, subnational, and local levels [17]. Achieving harmonisation thus requires not only methodological standardisation but also an objective, reproducible mechanism for assessing the maturity and readiness of monitoring techniques [18].

A concept to streamline monitoring plans has been proposed that uses Reproducible Analytical Pipelines (RAPs) and Technological Readiness Level (TRL) [19]. RAPs represent the core building blocks of a process, providing a structured methodology for automating each step in the production of scientific output. The UK Office for Statistics Regulation in 2017, emphasized RAPs as a mechanism to achieve the highest standards of trustworthiness and quality in official statistics [20]. Originally adopted in computational sciences, RAPs recognised that computers, though seemingly error-free, require rigor in algorithm implementation. Early on, little attention was paid to reproducibility, software and hardware variability, or how difficult it could be to reconstruct working pipelines. Soon, computer scientists understood that all data and code must be openly accessible to enable reproducible computation [21]. This recognition catalysed the development of Open Access software and FAIR (Findable, Accessible, Interoperable, Reusable) data principles [22], reinforcing RAPs roots in software engineering. RAPs have since emerged as a powerful framework for creating robust, repeatable workflows, capable of saving time and financial resources. Their application now extends to fields such as microbiology [23], virology [24] and eDNA-based species identification [25], among others.

In plastic pollution monitoring, RAPs delineate each key analytical step from sample collection to data reporting, into clearly defined segments. This modular structure facilitates transparency, enables accountability, and enhances understanding among scientists and stakeholders alike [19]. It also supports policy-making by delivering traceable and transparent data. There is currently no standardised framework for defining RAPs in plastic pollution monitoring, as this represents a novel application. As such, methods developed in statistics or computer science cannot be directly applied and statistical programmes such as R or Python are not yet suitable for these assessments (Ben Marwick and Mullen, [26]). For plastic analysis, RAPs are developed through expert consensus informed by literature reviews. While certain aspects of the workflow have been defined (e.g., Primpke et al., [27], the development of comprehensive analytical pipelines for plastics of varying sizes and across different environmental compartments remains incomplete. A synthetic index can be a valuable tool for evaluating and defining the maturity level of individual steps within a RAP.

Technological maturity is essential for distinguishing between proven capability and theoretical potential. Maturity can also be conceptualized as the position within a technology lifecycle, from the experimental stage to large scale exploitation, akin to stages in biological development [28, 29]. Originally developed by NASA in the 1970s, the TRL scale ranks technological maturity from 1 (basic principles) to 9 (fully mature, deployable technologies). Though developed for space applications, it has since been adopted by engineering, chemical industries, and EU innovation policy, particularly within Horizon Europe research programs (Commission Decision C

(2017)7124) [30]. While the TRL scale is not always easily applicable to non-physical or conceptual frameworks [31], its application to plastic science is emerging. For instance, TRL has been used in assessing technologies for chemical recycling of household plastics [32], composites recycling technologies [33], hospital plastic waste management [34] and microbial plastics biodegradation [35] and can be invaluable in the choice of methods for monitoring. Applying TRL to RAPs introduces a promising strategy to evaluate the maturity of analytical steps, methods, and technologies [19]. For instance, a step with TRL > 6 may be deemed mature enough for inclusion in large-scale monitoring programs. Conversely, steps below TRL 3, cannot be considered suitable for monitoring plans and should be targeted for further R&D investment. TRL criteria in plastic pollution monitoring fundamentally differ from those used in traditional engineering applications, and at present expert-based evaluations constitute the essential and appropriate foundation for the assessment. Multiple recent studies have convincingly demonstrated that this TRL framework can be successfully and meaningfully applied to plastic pollution research [19, 36–38].

A Systematic Review (SR) can be used to assess the development of methods, across scientific and grey literature as it provides a rigorous synthesis designed to answer specific research questions through comprehensive literature analysis, using pre-defined eligibility and selection criteria. SRs incorporate an explicit layer of methodological systematisation, improving transparency and reproducibility to the review process [39]. Recently, SRs on plastic pollution have begun to emerge, focusing on ecological effects [40], specific habitats [7, 41–43], and animal groups [44]. Other reviews addressed sediments [37, 45], and challenges in long-term monitoring [46]. These efforts underscore the need for dedicated support tools capable of navigating the growing literature base with robust methodologies. However, no comprehensive SR has yet evaluated the full scope of plastic monitoring methodologies across all size classes and environmental matrices.

To fill this gap, we systematically reviewed the plastic pollution literature encompassing both peer-reviewed and grey literature sources. The systematic review was carried out in 2022, and the dataset included publications from 1960 to 2021, the most recent year for which indexing could be considered complete. This decision was made to avoid uncertainties associated with in-press or partially indexed studies and follows PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidance on defining and reporting search timeframes.

Here we outline the SR protocol and introduce an Open Access database that is freely available online for consultation and reuse. We aim to demonstrate its utility through case study applications addressing cross-matrix questions of broad relevance, while matrix-specific meta-analyses are explored in companion papers within this volume. Additionally, we present new perspectives on evaluating plastic pollution monitoring methods by applying the TRL and RAP frameworks.

Methods

Mandate, preparatory phase and protocol definition

The mandate of this SR was to build a database of scientific papers to define the current state of knowledge on methods used to measure and monitor the abundance of macro-, micro-, and nano-plastics in water, sediments, biota, and air. The workflow was developed based on the key steps for SRs provided by Pollock and Berge [47] and Alexander [48], alongside guidelines from the Cornell University (https://guides.library.cornell.edu/evidence-synthesis/steps) and the University of Maryland (https://lib.guides.umd.edu/SR/steps). The PRISMA framework was adopted, and the checklist of items used is shown in Fig. 1.

For the purposes of this SR, the following definitions were adopted:

- Plastic: Materials composed of polymers, possibly with additives, that serve as structural components of finished products—excluding unmodified natural polymers. Definitions align with EU Directive (2019/904) and ISO 472:2013, though inconsistencies exist: for example, the EU excludes coatings/paints, while ISO excludes certain elastomers. Further discussion is available in Hartmann et al., [49] and Kershaw et al., [11].
- Litter: Persistent, manufactured, or processed solid materials discarded or abandoned in the natural environment [50]. Although “litter” and “debris” are often used interchangeably, we chose “litter” for its greater communicative impact in public discourse, highlighting the urgency of preventing environmental pollution.

Size classification of plastics is also debated [11]. Operational subcategories reflect sampling and detection limitations. For instance, the Arctic Monitoring and Assessment Programme guidelines [51] define distinct size classes for water and sediment. While microplastics are often subdivided using different schemes [52], this SR follows the general definitions in ISO/TR 21960:2020 (see Table A1).

Task groups of reader pairs were created based on their expertise in specific environmental matrices (water, sediment, biota, air). Each group read papers and contributed to the selection of relevant keywords and search strings.

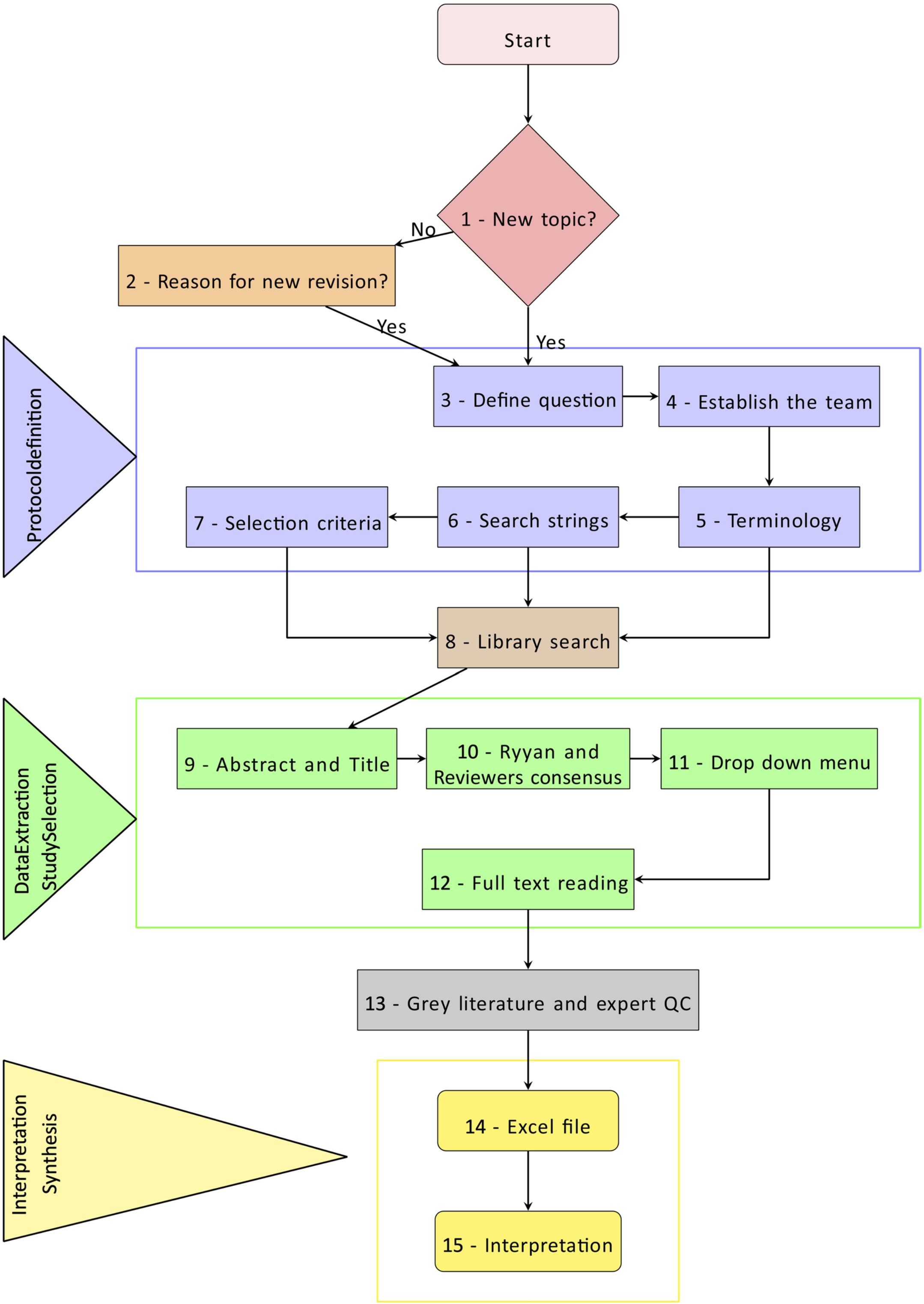

Fig. 1 PRISMA flow chart for our SR

Before the selection process, all participants received educational materials on scientific papers reading techniques to harmonise quality and standardise data extraction procedures [53–55].

Search string generation and selection criteria

A data-mining protocol using matrix-specific search terms and search strings to query relevant databases was developed. The search was limited to original papers written in English, published in peer-reviewed literature and indexed in Scopus and Web of Science databases in (Supplement B2). Search terms were defined by expert groups and keywords lists were created for each matrix/task group (Supplement C3). Keywords were merged into a single list to form the query string. The final search was conducted by a professional Librarian. Review articles and publications lacking the exclusion criteria summarised in Supplement D4 were excluded. Grey literature was handled separately.

Library search

The librarian at the University of Oslo performed the search. Articles published in English from 1960 to March 2021 and indexed in SCOPUS were considered eligible for analysis if the selected keywords appeared in the title or abstract. Given the exceptionally large number of publications retrieved through SCOPUS ($n = 3{,}290$), which is widely recognized for its broad coverage and strong representation of peer-reviewed literature, the inclusion of additional bibliographic databases (e.g. Web of Science, ScienceDirect, etc.), was not expected to substantially increase the evidence base. Rather, it would likely have introduced a high degree of redundancy, reduced data manageability, and increased screening workload to unsustainable levels. This approach is consistent with PRISMA recommendations, which allow the use of a single comprehensive database when justified by the scope, volume, and objectives of the systematic review. Criteria for selection of papers are reported in Supplement C3.

Abstract and title screening

Readers were divided into seven pairs from different institutes with different expertise in the field of plastic pollution and with their own set of titles/abstracts to screen. Each group evaluated papers against the inclusion criteria, tagging relevant papers according to the relevant environmental matrix. The open-source software Rayyan (https://www.rayyan.ai/) was used to manage citation screening [56]. Extracted data from each paper was compiled in Microsoft Excel. Readers first worked independently using Rayyan's blind mode. Once both readers had screened all papers, they resolved discrepancies by consensus, and non-relevant papers were removed. The eligibility criteria (inclusion and exclusion criteria) applied at this stage are fully reported in Supplement E5.

Dropdown menus and full text reading

Standardised dropdown menus were created in Excel to guide and unify data extraction across papers and matrices. The full list of dropdown options is reported in Supplement G6. Each reader compiled their individual file, and disagreements were resolved through collaborative consensus.

Grey literature and quality control

National and international networks helped identify 44 English-language grey literature reports. After screening, 33 reports were included and reviewed using the same protocol as peer-reviewed papers to extract relevant information for all four matrices. Guidelines and recommendations on plastic monitoring were reviewed separately to map international and national monitoring strategies, though they were not included in the SR itself.

Three QA/QC checkpoints were integrated into the SR process:

1. Duplicate identification.
2. Cross-checking literature search against expert-provided references: 78% of expert-suggested papers were included, exceeding the 60% quality threshold.
3. Title Screening losses: three papers were lost because they were erroneously identified as review articles.

At each check point the inclusion or exclusion of significant literature was assessed by comparing it to a literature list provide by experts. All QA/QC procedures were handled separately from the SR by an independent reviewer, and results were withheld from the main SR team until later stages to ensure maximal objectivity.

Excel compilation and data analysis

Each matrix had a dedicated Excel file, which was later merged into a single master worksheet. The full dataset is openly available through Zenodo (https://doi.org/10.5281/zenodo.10680679). Data analysis was conducted using Excel, PAST, Octave and R software.

Reproducible Analytical Pipelines (RAPs)

Plastic monitoring consists of a sequence of common and fundamental steps, referred to as RAPs. These RAPs capture essential phases across different environmental matrices. Building a RAP can get advantage of computer programs and codes [57], but no standardised tool exists for plastic monitoring. RAPs were identified through experts' consensus following the SR analysis. All selected RAP components are available in the Excel dropdown menus.

TRL evaluation criteria according to ISO 9126 Quality model

The TRL framework ranging from 1 to 9 lines up with broader categories such as ”basic research”, ”feasibility”, ”development”, and ”demonstration”. Our adaptation aligns with these principles, but tailor TRL descriptions to plastic monitoring workflows. TRL scoring was informed by the ISO 9126-1 software quality model [58], part of the ISO 9000 family, which is the most important standard for quality assurance. Quality is defined as the set of attributes that determine a system's ability to meet specified requirements. It provides a hierarchical structure, criteria for evaluation, comprehensive expressions and terms, simple and accurate definitions [59]. This model includes six major criteria: Functionality, Reliability, Usability, Efficiency, Maintainability and Portability [58]. Compliance with each assessment criterion is defined and systematically evaluated. In accordance with established ISO/EC TRL frameworks, each criterion is scored on a scale from 1 to 7, and the mean score is used to derive the overall TRL that serves as the basis for expert evaluation. Each criterion requires a dedicated analysis to define the corresponding ranking, and expert judgement is also supported by the outcomes of the SR (Fig. 2). It is also possible to use weighted averages to reflect the relative importance of specific criteria if experts' consensus should consider specific criteria more relevant than others.

TRL can be applied broadly to entire plastic monitoring guidelines, but its use at individual RAP step level has the potential to greatly improve and accelerate the selection, evaluation, and adoption of large-scale plastic monitoring programmes [19]. A pragmatic TRL assessment of the RAPs was based on the number of references citing each method in the SR. For instance:

- TRL 4–5: Methods validated at the laboratory level with > 10 entries in the SR from different research groups.
- TRL ≥ 6: > 20 entries in the SR, potentially suitable for deployment in large-scale monitoring programs (though not necessarily the most innovative or efficient method).

This scoring approach evaluates operational readiness, but it is not quantitative and does not assess its value for monitoring plans. A method must also be assessed for compliance, i.e. the degree to which the method adheres to established standards, regulations, or specifications. In quality models (such as ISO/IEC 9126 or ISO/IEC 25010), compliance ensures that the method meets mandatory requirements.

Results and discussion

Systematic review

The query returned 3290 papers matching one or more of the selected search terms. Titles and keywords of all papers were reviewed during a first-level quality control, resulting in the exclusion of 861 non-relevant papers.

A total of 2429 papers were retained and distributed among task groups. Each reader screened titles and abstracts of approximately 400 papers. During QA/QC, nine papers suggested by experts were found to be absent from the primary literature search. In five of these cases, exclusion was likely due to the presence of terms like "*accumulation*", "*ecotoxicology*", "*effect*", "*exposure*" and "*risk*", which matched the exclusion criteria. It was not possible to determine why the remaining four papers were excluded. Two additional records, initially tagged as modelling studies, were later excluded. These papers included elements of modelling, but were both based on field data. A summary of the number of papers for each compartment is provided in Fig. 3.

The blind review process was completed by all seven reader pairs. Each reader categorized entries as "*include*", "*exclude*" or "*maybe*" (Supplement E5). Conflict rates between paired reviewers ranged from 8% to 22%, with consensus achieved in all cases following discussion. The final average inclusion rate was 76% (range: 71–85%). Expert validation further supported quality assurance, including an assessment of scientific quality and methodological completeness. A summary of Rayyan outputs is reported in Supplement F.

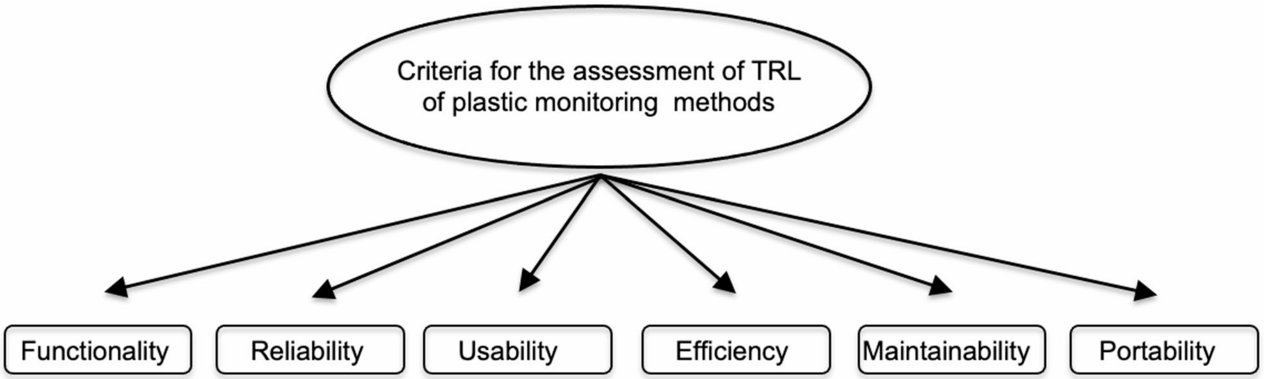

Fig. 2 Criteria for the assessment of TRL of plastic monitoring methods based on ISO 9126 Quality model. Compliance with each criterion is defined and systematically assessed. Each criterion is assigned a score on a scale from 1 to 7, consistent with established TRL definitions, and the resulting average score is used to derive the TRL, serving as the basis for expert evaluation

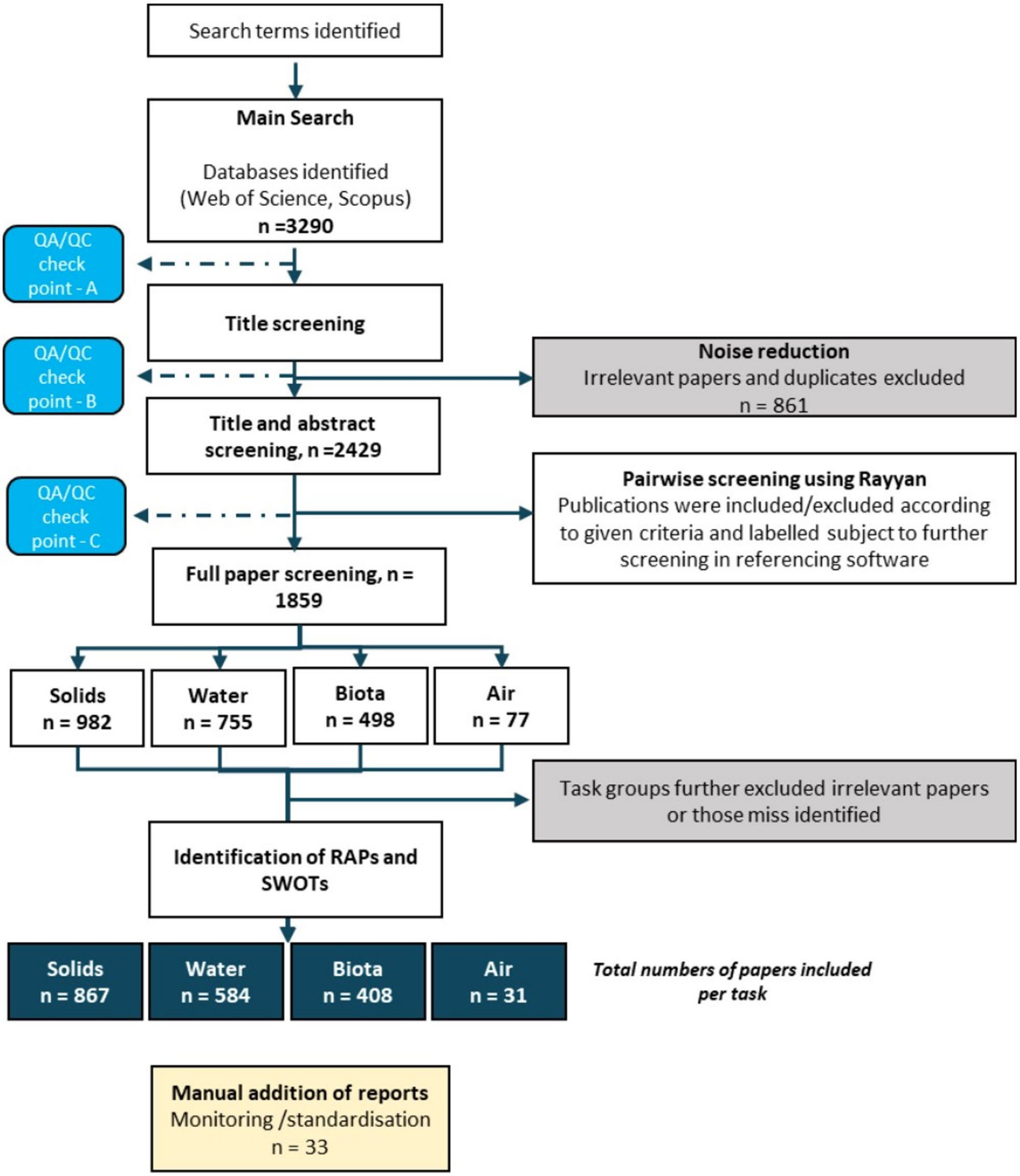

Fig. 3 Overview of Systematic Review (SR) steps to formulate the literature database used for the identification of Reproducible Analytical Pipelines (RAPs). The numbers refer to the total number of papers collected and analysed at each step. Some papers were relevant for more than one of the task groups. Grey literature did not undergo the full SR, but RAPs were identified. Papers about air pollution were too scant to be considered

Historical trends in plastic monitoring studies

The oldest record in the SR was by Merrell [60]. While earlier works exist, such as Carpenter and Smith [61], Nicholson and Leighton [62] and Shubik et al., [63], these were excluded because they focused on plastic toxicity or general observations, rather than environmental monitoring. Since 1980, publication output has grown steadily across all environmental compartments (Fig. 4), with

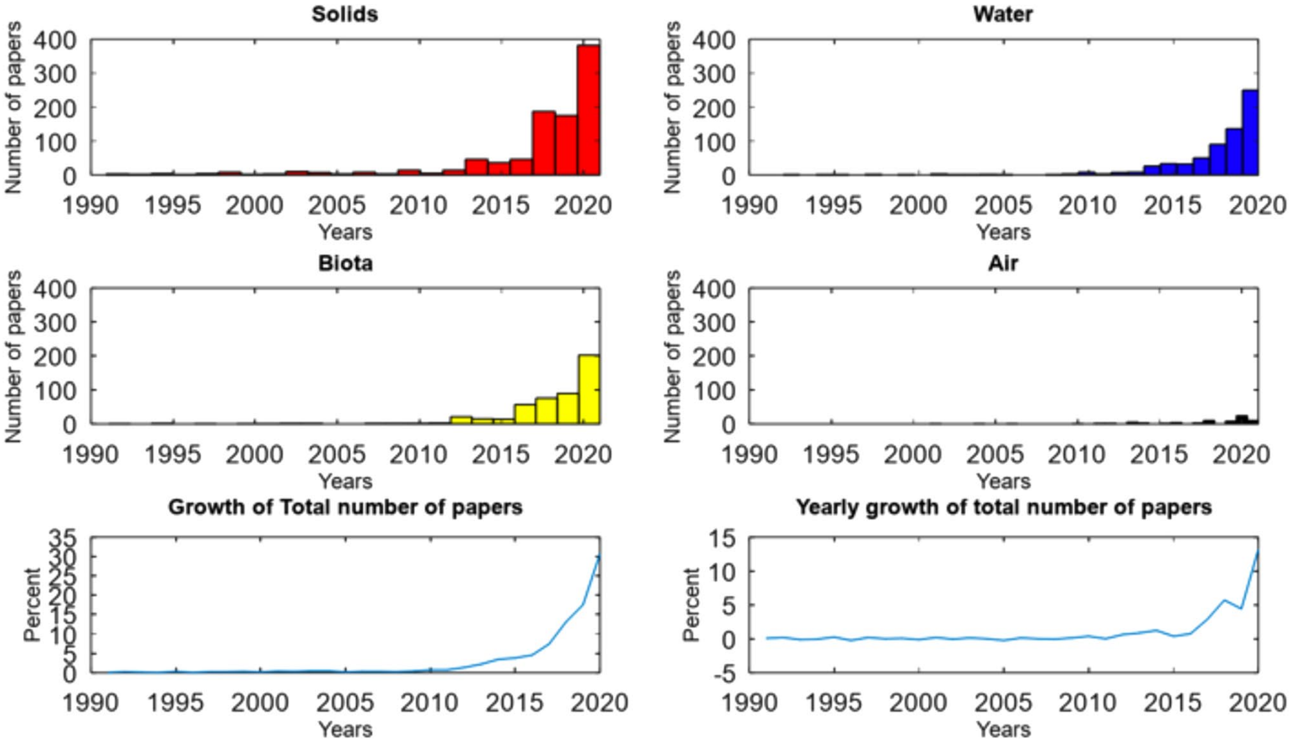

Fig. 4 Number of peer-reviewed articles about plastic monitoring in scientific literature published every year from 1990 to 2020 in different matrices. Year 2021 is not reported here because data does not cover the full year. Percent growth of the total number of papers since 1990 and yearly trend. The growth rate of papers on plastic monitoring after 2010 was higher than the typical rate of a generic field of science expected from bibliographic models

sediments-related studies (including beach and deep-sea environments) being the most abundant. The annual growth rate increased exponentially in recent years (Fig. 4), particularly in 2020, showing a 10% increase in publications relative to the previous year, similarly to what was found by earlier research [42, 64, 65]. This exceeds the average annual scientific publication growth rate of 5.6% [66]. Notably, the observed growth rate also surpasses predictive models for average scientific output [67], highlighting the rapid expansion of interest in plastic monitoring after 2010. Plastic pollution in the air was understudied, and number of papers were not enough for a SR.

Distribution of papers per geographic area and plastic sizes

The geographic distribution of plastic monitoring studies over the past two decades has been uneven. Asia and Europe accounted for the majority of literature, with comparable publication number but distinct focal areas: water-based monitoring dominated in Asia, while sediment-focused studies were more prevalent in Europe. Other regions, particularly polar areas, remain significantly underrepresented (Fig. 5). Microplastics (< 5 mm) are the most frequently studied size class across all compartments: water (1477 studies), sediments (1121), and biota (890). Macroplastics were primarily investigated in sediments (587 studies), including beach sediments, which are widely monitored globally. In contrast, macroplastic studies in water (132) and biota (33) were relatively scarce. Nanoplastics received minimal attention, with only 13 studies in water, 3 in sediment, and 4 in biota. Airborne plastics were also markedly understudied, represented by just 31 publications. Some studies covered multiple size categories, and the entries for the analytical pipelines were therefore disaggregated.

RAPs in plastic monitoring

Across the reviewed literature, six core steps consistently emerged in plastic monitoring workflows, forming the basis of the framework for Reproducible Analytical Pipelines (RAPs) (Fig. 6). Matrix-specific factors primarily influence the earlier stages of sampling and sample preparation, whereas post-extraction protocols tend to converge and are influenced more by particle size than by environmental compartment.

- *Survey design*. Survey design refers to the systematic planning of sampling and data collection strategies. Despite its critical role in ensuring cost-efficiency, validity and transferability of the results [68], it is often underreported, or poorly described in the reviewed literature. Key elements include sampling frequency (e.g., single vs. repeated), study objectives (research vs. monitoring), and alignment with standardised protocols (e.g., OSPAR,

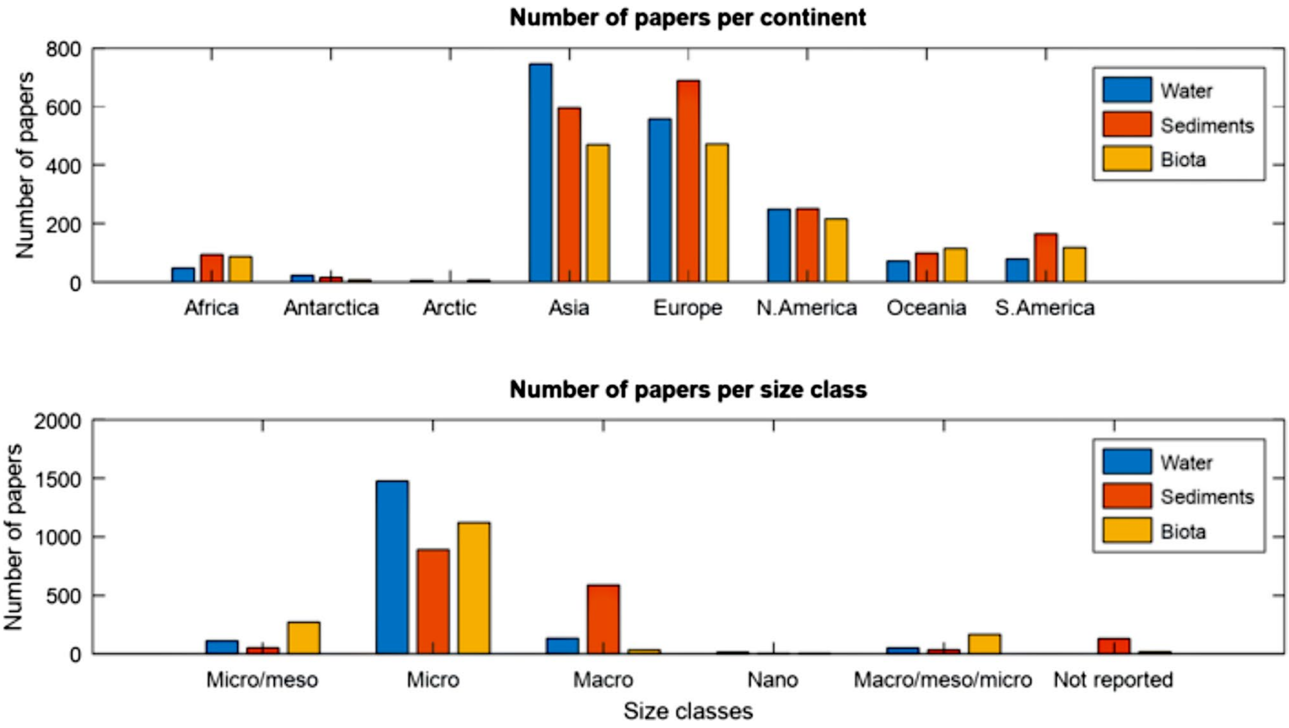

Fig. 5 Above is the number of peer-reviewed scientific publications on monitoring per continent, and below the number of papers per size classes. Some papers combined different size classes, making it impossible to assign them to a specific category

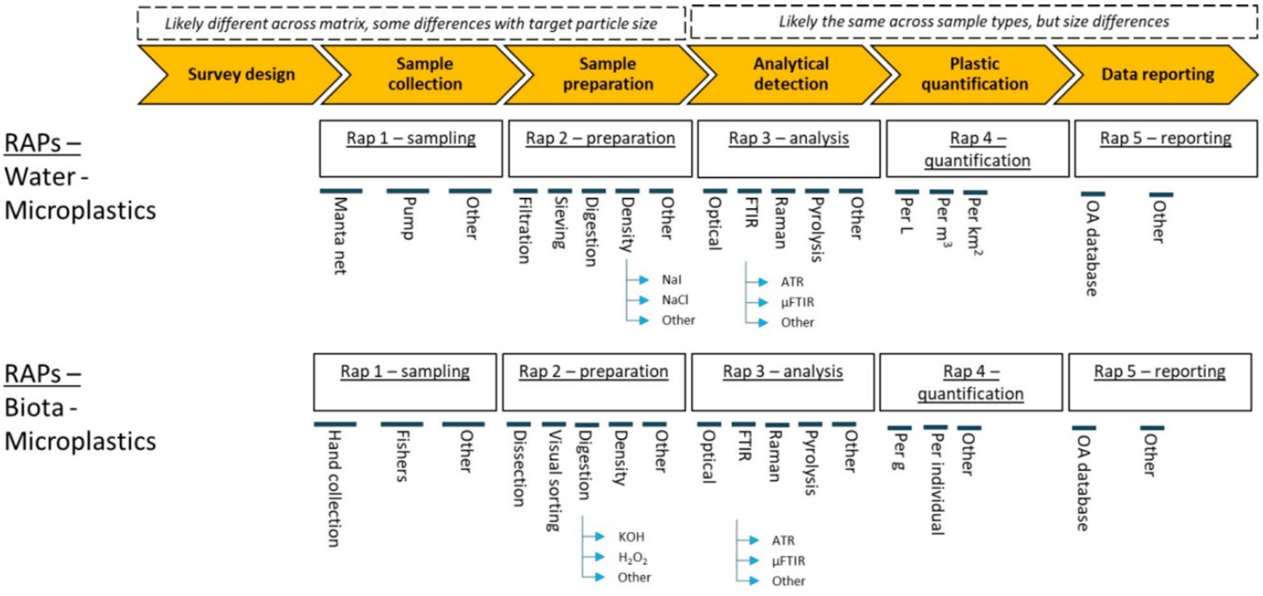

Fig. 6 Examples of Reproducible Analytical Pipelines (RAPs) for the assessments of plastics in water and biota

MSFD, NOAA). Monitoring was the stated objective of 83 sediment, 278 water, and 22 biota studies. Method development was a common aim across all matrices, with 165 publications for sediments, 218 for water, and 238 for biota. The remaining categories, i.e., "*Other*" and "*Citizen Science*," represented minor categories across all sample types (Fig. 7). Once the study objective is defined, a sampling plan must be developed to accurately represent the target population. This involves selecting an appropriate strategy: *Random Sampling* ensures equal selection probability across sampling units, minimising bias; *Systematic Sampling* collects samples at regular intervals, offering consistent spatio-temporal coverage; *Stratified Sampling* divides the study area into distinct

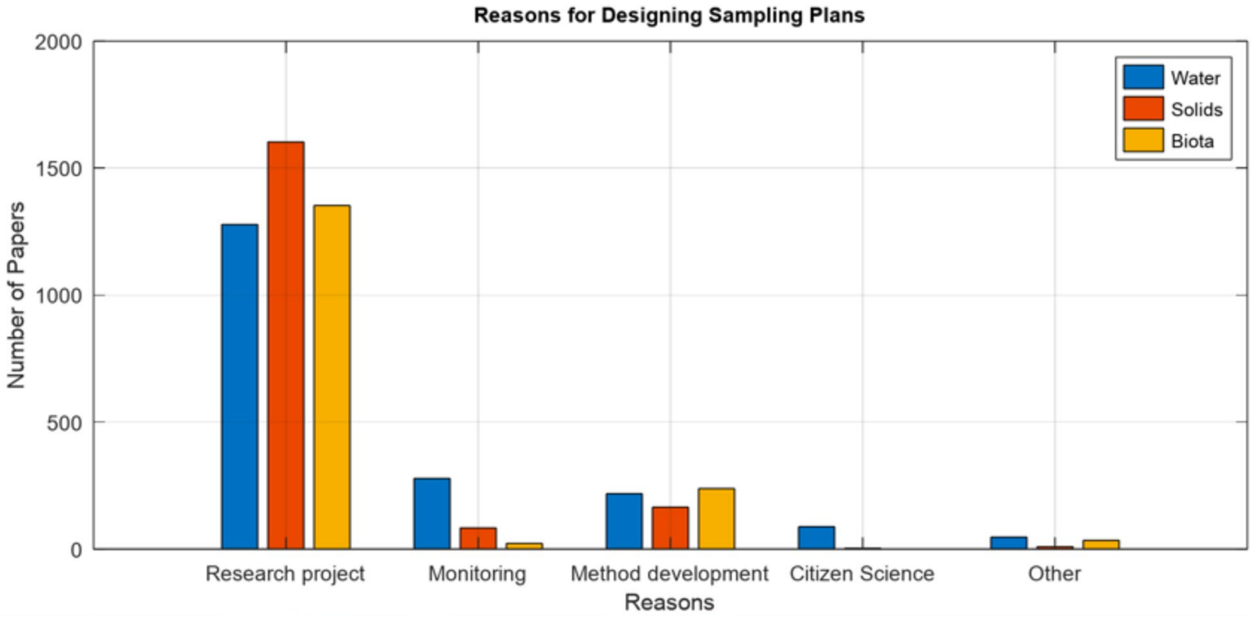

Fig. 7 Distribution of reasons for designing sampling plans across different matrices (Sediments, Water, and Biota)

strata (e.g., habitat types) to ensure representation across varying different conditions; and, *Adaptive Sampling* adjusts sampling intensity based on real-time findings, such as increasing sampling effort in high-density areas. A comparative summary of these approaches is provided in Berndt [69]. Despite their relevance, these strategies were rarely described explicitly in the reviewed literature. Survey design was typically shaped by context-specific factors, including research questions, target population, and study goals. No universally harmonised approach was identified across studies.

- *Sample collection.* Sample collection is the stage at which matrices/samples containing plastic particles are collected for subsequent analysis. Methods are matrix-specific: corers and grabs for sediments, nets and pumps for water; fallout passive collectors and active samplers are used for air; and dissection or whole-organism collection for biota. As a foundational component of plastic pollution research, sample collection is widely discussed in research papers and methodological manuals and guidelines. However, many studies lack essential details, such as GPS coordinates, sample size, and use of procedural blanks. The missing details compromise reproducibility from the early steps of the analytical pipeline. Critical parameters including adequate sample size, replication, contamination controls, preservation techniques, and procedural blanks, were frequently omitted across all matrices, especially in older studies. Although comprehensive reporting on sampling remains limited, recent studies show improvements in documentation. Innovations are expanding sampling capabilities, notably through autonomous underwater vehicles (AUVs) [70], drones for remote access [71], satellite-based detection ([72, 73], and citizen science initiatives for large-scale data collection [74].
- *Sample preparation.* Sample preparation involves isolating plastic particles from their surrounding matrix while minimising contamination [75]. Procedures vary by environmental compartment (see Fig. 6 for some examples), but contamination control is universally critical. Recommended practices include the use of non-plastic materials (e.g., stainless steel or glass), cotton laboratory coats to reduce synthetic fibres shedding, nitrile gloves, and procedural blanks. Working in clean environments, such as clean rooms or laminar flow hoods, is essential to prevent airborne contamination. Proper sample labelling and storage (e.g., including date, location, matrix type) should also be followed. Preservation is typically achieved through freezing or drying, although the use of preservatives such as alcohol or formaldehyde is also common. Notably, many studies failed to report contamination risks associated with fixing solutions. Pretreatment via filtration is commonly employed to remove the matrix before concentrating samples onto filters. Minimal pretreatment is required for low particle load samples, such as tap water or air, whereas biota, sediment or water samples with high amounts of natural materials necessitate more elaborate pretreatment protocols. Digestion of organic matter and density separation are frequently applied to isolate plastic particles. Density separation is performed using solutions of varying densities, including hypersaline NaCl, NaI, $ZnCl_2$, or NaBr. The resulting particle fraction is typically concentrated onto a filter for subsequent chemical analysis.

- *Analytical detection* Analytical detection focuses on minimising false positives and identifying the chemical composition of isolated particles. As particle separation is completed in earlier stages, subsequent steps in the RAP are largely matrix-independent and applicable regardless of the sampled matrix. For macroplastics, polymer identification is typically straightforward, aided by product labels and polymer stamps, which reduces the likelihood of errors. In contrast, many older microplastic studies lacked robust chemical characterisation, relying instead on visual identification and researcher judgement. This approach led to inaccurate polymer quantification and raises concerns about the reliability of legacy data. Simple techniques such as the "*hot-needle test*", which identified plastics based on melting behaviour, were commonly used in the past. Whilst this method occasionally aligned with up to 90% of Fourier Transform Infrared (FTIR) spectroscopy results [76], it does not provide quantitative data or determine polymer type. Accurate polymer identification is essential for monitoring, particularly when evaluating the effectiveness of mitigation policies targeting specific polymers. Reliable and replicable techniques, such as FTIR- and Raman spectroscopy, pyrolysis coupled with gas chromatography/mass spectrometry, and other advanced methods, are widely employed to ensure consistency and precision in polymer identification. Although alternative approaches exist, they are not routinely used for monitoring purposes. Many studies would have benefited from more detailed reporting of analytical protocols and instrument detection limits to enhance reproducibility. A reliability reassessment is recommended before comparing historical data with contemporary findings.

Quantification and measurement units

Quantification involves counting and size/shape characterization plastic particles to assess their abundance in the environment. This process often requires microscopy or automated imaging systems, particularly for smaller particles such as small microplastics (< 200–300 μm) and nanoplastics. Mass measurements are typically performed using high-precision balances, with care taken to exclude non-plastic debris and organic matter. Combined, these approaches enable the calculation of key metrics including particle size distribution, average particle mass, and total plastic concentration.

Units of measurement are fundamental in scientific research, yet our systematic review revealed that there is currently no harmonised global standard for reporting units. A wide range of units was employed across studies (Fig. 8), impairing data comparability. Most publications reported macroplastic counts per area (38%), per survey (16%), or per transect length (14%). Only 16% used mass-based units, and 1% used volume-based units. The remaining 17% used other units such as fluxes or relative composition. This inconsistency underscores the urgent need for harmonisation [11]. While this section provides an overview of unit diversity, identifying optimal units for each matrix and size class requires dedicated studies. Harmonising units is essential to enable interoperable and comparable datasets. For microplastics, most studies reported data with units/metrics based on particle counts per either sample weight (54%), volume (6%) or area / survey length (13%), with only 6% using mass-based units for solid samples. Mesoplastics followed trends, with counts per area (32%), survey length (13%) or sample weight (10%) being most common; 16% of the publications used mass-based units (Fig. 8). A coordinated effort

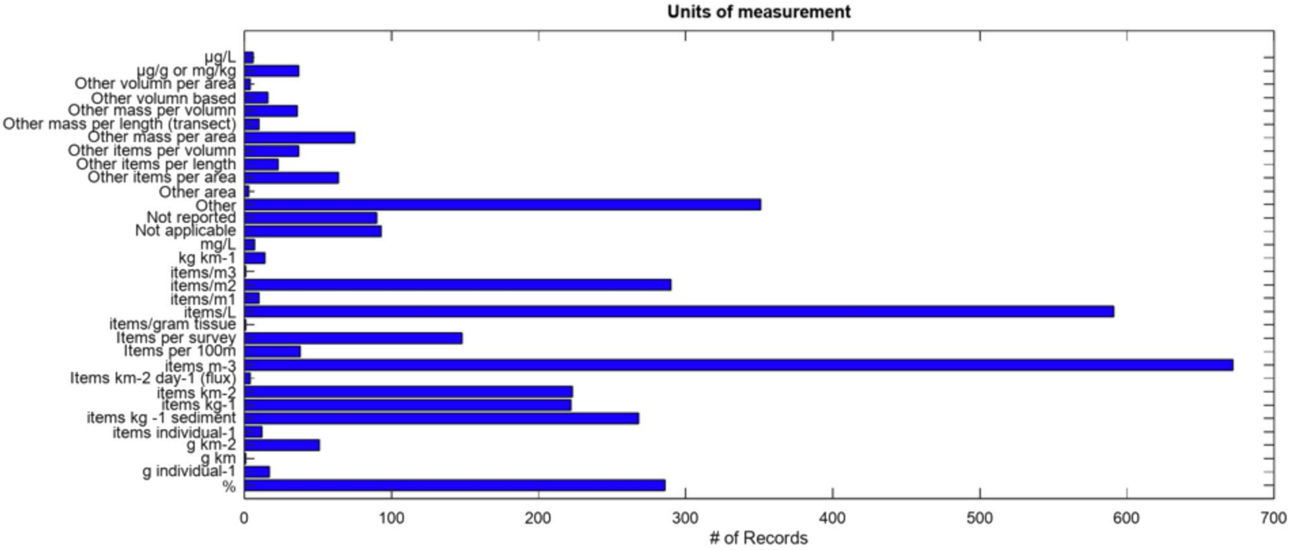

Fig. 8 List of measurement units used to quantify plastics in monitoring studies of water, sediment, biota and air, as found during the SR

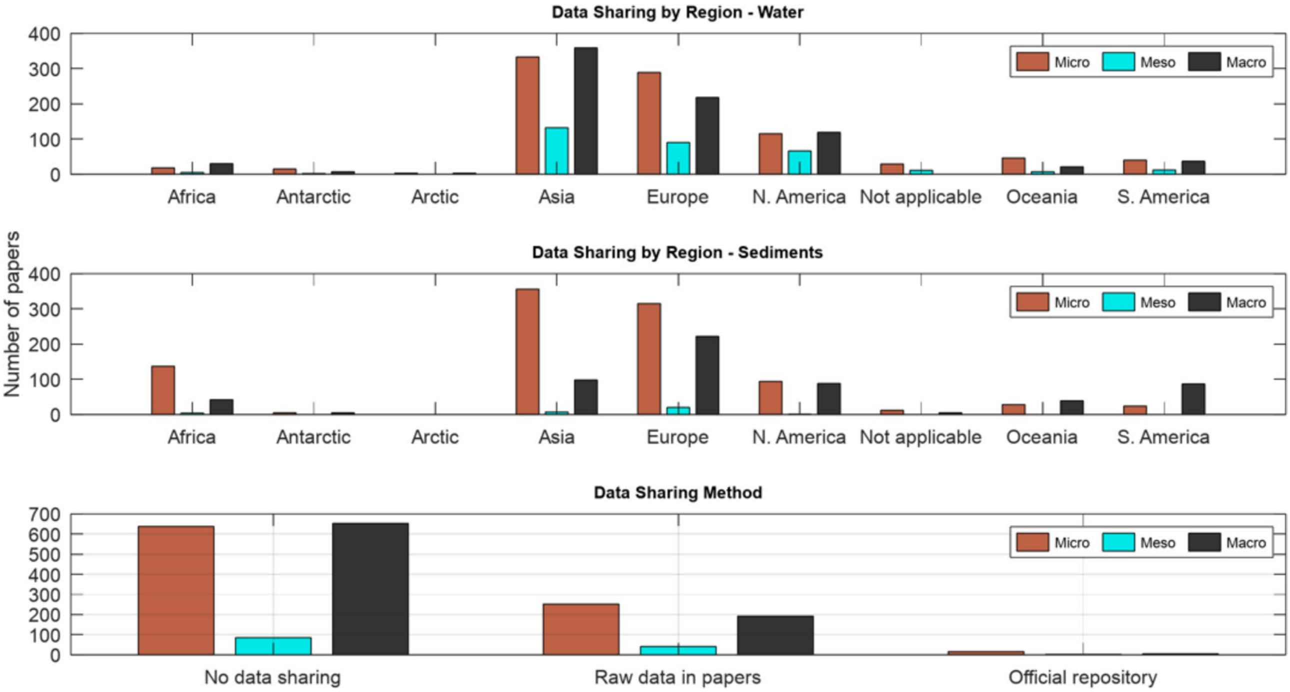

Fig. 9 Percent of data sharing from papers on micro- meso- and macroplastics in water and sediments from different continents and data sharing method

to harmonise reporting across size classes and environmental compartments is urgently needed.

Data reporting and FAIR principles

Data transparency remains a major bottleneck in plastic pollution research (Fig. 9). Our systematic review revealed that 67% of microplastic studies did not share data, 28% included raw data within publications or supplementary materials, and only 2% deposited data in external repositories. For mesoplastics, 64% withheld data, 33% provided raw datasets, and just 1% uploaded data to repositories, although none of which were international open-access platforms. Overall, 71% of studies failed to provide accessible datasets. Only 26% included raw data, and a mere 4% deposited data in established international repositories (e.g., OSPAR, ICES, NOAA, or EMODnet). Long-term data management and adherence to FAIR principles (Findability, Accessibility, Interoperability, and Reusability) were rarely addressed, highlighting the need for improved data sharing practices and infrastructure to support transparency and reproducibility. These findings underscore the urgent need for harmonised data management protocols encompassing reporting standards, data treatment, storage, and long-term availability. Despite the recognised importance of FAIR compliance, the literature on plastic pollution data management remains sparse. Establishing robust, harmonised data reporting frameworks is therefore crucial to ensure interoperability and comparability across monitoring efforts.

Conclusions

This systematic review analysed 1,859 peer-reviewed publications out of an initial pool of 3,290, identifying key trends, methodological gaps, and persistent challenges in plastic pollution monitoring. This study provides a foundation for a global framework to select and implement harmonised plastic monitoring methods. The research landscape remains geographically uneven, with a concentration of studies in the OSPAR region, the Mediterranean, and Asia, while other areas, such as the Black Sea and South America, are notably underrepresented, particularly in biota-focused research.

Methodological reproducibility continues to be a critical issue; many studies lack sufficient detail to enable reconstruction of techniques, with inadequate reporting of sampling procedures, reagent specifications, and locations undermining scientific rigour and data comparability. The fact that different papers use different approaches to state the lower limit (filter pore size, versus real method lower limit) further complicates the scenario. The intrinsic size-dependent nature of plastic debris precludes a universal analytical approach, necessitating distinct methodologies for different size classes and creating barriers to standardisation.

A substantial portion of the literature, especially older publications, did not align with current methodological guidelines at the time of publication. Researchers often replicate legacy methods or rely on outdated techniques in long-term monitoring programmes to maintain data continuity, despite the availability of improved protocols. Although recent studies show better adherence to contemporary standards, ensuring compatibility with historical datasets remains essential. Data sharing is also limited: only a minority of studies provide full dataset accessibility, and few deposit data in open-access repositories, impeding transparency and reuse.

The rapid expansion of plastic pollution research has led to a proliferation of analytical protocols, contributing to divergence in Reproducible Analytical Pipelines (RAPs). Airborne plastics and nanoplastics remain underexplored, with insufficient data to support methodological harmonisation. Quality assurance and control (QA/QC) procedures are frequently absent or poorly documented, particularly in microplastic studies, where filtration systems and positive controls are often inadequately reported. Contamination sources are rarely distinguished, and minimum particle size detection limits are inconsistently specified.

The lack of harmonisation in reporting units, for instance the use of mean versus median values, further complicates data interpretation and cross-study comparisons. TRL scores are encouraged in accompanying papers for each compartment. But so far, TRL evaluations are subjective and potentially biased by different opinions by experts. Stakeholders may also advocate for one technology over others, leading to unbalanced estimates.

We have to clarify that the TRL assessment derived using the method presented here is based on the state of the literature at the time of analysis. Given the rapidly expanding research activity in this field, future studies and updated systematic reviews will allow the TRL assessment to be progressively refined and strengthened. We also note that continued methodological development toward more data-driven and quantitative approaches, complementing expert judgment, would represent a valuable direction for future research.

We highlight the need for a weighted, semi-quantitative TRL framework that incorporates usage frequency, reproducibility, and maturity into an even more objective framework to promote transparent, evidence-based standardisation of monitoring methods. These measures are essential to improve the transparency, reproducibility, and global comparability of plastic pollution monitoring. The paper of Vanavermaete et al., [38] is a representative case study of the practical application of TRLs in the context of monitoring plastic pollution in biota and exemplifies how TRL can be effectively employed to assess the maturity and deployment potential of emerging technologies in environmental science. This approach not only enhances the strategic planning of research and development efforts but also supports evidence-based decision-making in environmental policy and management. Future harmonisation efforts should prioritise developing interoperable data standards, matrix-specific reference methods, and a semi-quantitative TRL index validated through expert consensus. These measures will support transparent, evidence-based decision-making and accelerate the transition from fragmented methodologies to globally comparable plastic pollution assessments.

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

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Author contributions
SA: Conceptualization, Validation, Methodology, Formal analysis, Data curation, Visualisation, Investigation, Resources, Writing and editing, Project administration. AL: Conceptualization, Validation, Methodology, Formal analysis, Data curation, Visualisation, Investigation, Resources, Writing and editing, Project administration. GS: Conceptualization, Validation, Methodology, Formal analysis, Data curation, Visualisation, Investigation, Resources, Writing and editing, Project administration. SP: Conceptualization, Validation, Methodology, Investigation, Data curation, Writing and editing. BDW: Conceptualization, Validation, Methodology, Investigation, Data curation, Writing and editing. DV: Validation, Data curation, Investigation, Writing and editing. KV: Validation, Data curation, Investigation, Writing and editing. VN: Validation, Data curation, Investigation, Writing and editing. DH: Validation, Data curation, Investigation, Writing and editing. AP: Methodology, Validation, Data curation, Investigation, Writing and editing. VD: Methodology, Validation, Data curation, Investigation, Writing and editing. JS: Conceptualization, Methodology, Investigation, Writing Review and editing. VHDS: Validation, Data curation, Investigation, Writing and editing. FG: Conceptualization, Writing and editing. GH: Data curation, Visualisation. BVB: Writing, Approved final version, Supervision.

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Data availability
All raw data used for this review are publicly available on the web. Excel files are available on Zenodo at 10.5281/zenodo.10680679.

Code availability
Not applicable.

Materials availability
Not applicable.

Declarations

Ethics approval and consent to participate

No ethical issues apply. Authorships have been defined according to Springer Nature indications. https://support.springernature.com/en/support/solutions/articles/6000214118first-author-and-corresponding-author-defined.

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