Microplastics and Nanoplastics

RESEARCH

Open Access

Value for money: a cost-effectiveness analysis of microplastic analytics in seawater

Nelle Meyers[1,2,3*], Kathrin Kopke[4], Natalja Buhhalko[5], Karin Mattsson[6,7], Colin R. Janssen[3,8], Gert Everaert[1] and Bavo De Witte[2]

Abstract

The availability of many microplastic analysis methods is challenging for researchers and policy makers when tasked with choosing optimal methods for their research question and a given budget. In this study, a cost-effectiveness analysis of methods for microplastic analysis in seawater was performed using survey data acquired from experts. Total analysis cost per method was determined accounting for labour and equipment costs, while method effectiveness was scored based on their ability to confirm the plastic nature of particles, their minimum detectable particle size, and other parameters. Results were validated and discussed during two workshops with scientists and policy makers. The resulting predictive tools allow to identify the most cost-effective methods for specific scenarios, and their associated cost. They mark an important step towards a more effective and informed approach to monitoring and managing microplastic pollution in the marine environment, ultimately contributing to the protection of marine ecosystems and human health.

Keywords Microplastics, Cost-effectiveness analysis, Predictive tools, Marine environment, Monitoring, Analysis costs

Introduction

Plastic contamination is recognised as a global threat, with the potential to cause detrimental effects on organisms in various environmental matrices, such as air, water, soil, sediment, including humans [7, 11, 23, 44, 66, 72]. Microplastics, defined as plastic particles between 1 µm and 5 mm in size [5, 25], are a major component of plastic pollution in the oceans. Monitoring microplastics larger than 300 µm in surface waters has become a common practice in the EU due to the regulations of the European Union (EU) Marine Strategy Framework Directive (MSFD) [17]. Currently, nets with mesh sizes around 300 µm are the predominant devices for microplastic surface water sampling, especially for seawater in large basins [14]. When used in isolation it is clear that only floating particles are considered, and microplastics larger than the net mesh size are sampled and considered in the evaluation. Because of this, pumps are frequently used to sample particles below 300 µm in size. Despite some possible disadvantages such as inefficient replicate sampling, approximation of sample volumes, and the need for

*Correspondence:
Nelle Meyers
nelle.meyers@ilvo.vlaanderen.be
[1] Flanders Marine Institute (VLIZ), InnovOcean Campus, Jacobsenstraat 1, 8400 Ostend, Belgium
[2] Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), Animal Sciences Unit - Aquatic Environment and Quality, InnovOcean Campus, Jacobsenstraat 1, 8400 Ostend, Belgium
[3] Laboratory of Environmental Toxicology and Aquatic Ecology, Faculty of Bioscience Engineering, Ghent University, 9000 Ghent, Belgium
[4] SFI Research Centre for Energy, Climate and Marine Research and Innovation (MaREI), Beaufort Building, Environmental Research Institute, University College Cork, Ringaskiddy, Co. Cork P43 C573, Ireland
[5] Department of Marine Systems, Tallinn University of Technology, 12618 Tallinn, Estonia
[6] Department of Marine Sciences, University of Gothenburg, Kristineberg Marine Research Station, 451 78 Fiskebäckskil, Sweden
[7] IAEA Marine Environment Laboratories, 4a Quai Antoine 1er, 98000 Monaco, Principality of Monaco
[8] Blue Growth Research Lab, Ghent University, Bluebridge, Wetenschapspark 1, Ostend 8400, Belgium

calm weather conditions to function properly [45], nets are useful devices because they allow fast collection of microplastics from large volumes of water covering vast areas [50]. They are also relatively inexpensive, and they do not require electricity nor specialised expertise.

Significant advancements have been made in the identification and characterisation of microplastics in marine matrices during the past few decades. To address the needs of different monitoring and research goals, a myriad of microplastic analysis methods have been developed. These approaches range from simple light microscopy and particle-by-particle spectroscopy or imaging spectroscopy to thermal degradation methods [39] and various statistical algorithms and image analysis tool packages. As each method has its advantages and limitations, the choice of method depends on the research question and the matrix being analysed, as well as the financial means available [1]. The rapid development and use of these different analytical methods has resulted in a lack of comparability of results obtained in these studies, potentially hindering regulatory framework development due to differing estimates of microplastic abundance and size distribution. In addition, the availability of many methods for similar sampling and analysis objectives are a challenge for researchers when tasked with choosing an optimal method for their research question and matrix within a given budget. Moreover, many microplastic analysis methods used remain rather expensive and labour-intensive, limiting their use in regions with limited resources. This may result in a bias towards preferred approaches in some regions with limited research funds, thus affecting the objective assessment of global microplastic pollution levels. Key questions about microplastic pollution and its impacts persist, underscoring the need for standardised, cost-effective, and reliable analysis methods to support regulatory action and enhance our understanding of critical thresholds.

To compare relative costs and outcomes of two or more courses of action, a cost-effectiveness analysis (CEA) is often performed. This is frequently done in healthcare to evaluate costs and benefits of different interventions, treatments and programs [15, 21]. Performing a CEA of different microplastic analysis techniques involves comparing major costs related to equipment and labour with their effectiveness in terms of their ability to confirm the plastic nature of particles, their limit of detection (LOD), their ability to identify polymer type, or any other parameter of interest. The outcome of such analyses provides decision-makers with objective information that can be used to allocate financial resources efficiently and make informed decisions about which technique provides the most reliable result at the lowest cost [12].

In this study, performed within the JPI Oceans' Andromeda project (https://www.andromedaproject.net), we provide concrete and useful recommendations on the selection of microplastic analysis techniques in terms of their cost-effectivity. The aim of these recommendations is to support researchers, policy makers and other stakeholders when having to choose between different microplastic workflows. Data from an online survey of the knowledge and experiences of experts in the microplastic field was used to develop predictive tools [42] that allows users to identify the most cost-effective methods for specific scenarios, and to calculate the total analysis cost of each method. Results were discussed with scientific experts and policy makers during two workshops. With these results, the study sought to provide practical recommendations on which microplastic workflows offer the best value for money.

Materials & methods

Survey

To investigate the cost-effectiveness of commonly used microplastic detection and quantification techniques in seawater, an online survey was performed, compliant with the General Data Protection Regulation (GDPR). The survey was written in English and the survey data was collected through QuestionPro (www.questionpro.com) (see Appendix A). The survey was sent to various (European) microplastics expert groups (e.g. JPI Oceans sister projects focusing on microlitter and ICES Working Group on Marine Litter (WGML)), professional networks of the authors, and was distributed via social media (X, previously known as Twitter). Informed consent was obtained before the start of the survey, and data was collected from September to November 2022. In total, 56 persons initiated the questionnaire, where 31 persons provided answers to all questions. Nevertheless, after removing unrealistic data (see 2.2 Data analysis), all answers per question were used, regardless of whether the respondent completed the questionnaire or not.

The survey comprised two sections: 1) inquiries about the respondents demography, and 2) a theoretical, detailed microplastic sample acquisition scenario followed by questions on the respondents' analysis workflow to process and analyse such samples. The first section of the survey aimed to determine the socio-economic characteristics of the respondents (employment country, sector, position, and others). Within the second section of the survey, a detailed, theoretical scenario was developed where we described a situation in which five seawater samples were collected with a manta net targeting > 300 µm microplastics. This scenario was used to obtain information on microplastic analysis labour and equipment costs of the survey respondents through

specific questions, if they were to perform the exact same analysis in their laboratories.

In the theoretical scenario, for each of the five seawater samples, here called a batch of samples, the inside of the manta net was rinsed with 1 L of Milli-Q water which was then collected in a glass bottle using a metal funnel. Each of the five acquired seawater samples contained 50 microplastics of various polymer types and shapes within the size range of 300 - 1000 µm, and a suspended particulate matter (SPM) content of 25 mg/L [46]. Respondents were asked not to take into account negative and positive control samples. Here, details of the respondents' microplastic analysis workflow were investigated, focusing on the sample acquisition, sample processing (preparing the sample for microplastic analysis), and sample analysis step (analysis of the actual microplastic content). This section of the survey aimed to determine two types of costs; the equipment costs, and labour costs. To do so, questions targeted the types of equipment participants used to analyse one batch of seawater samples as defined above, as well as the equipment purchase prices (excluding VAT)/renting costs, the man hours (working hours) needed for each step within the workflow as well as the contract types of the people performing the analysis steps, the median gross annual salary of 1) senior researchers and 2) lab technicians with ten years of work experience in the country of employment of the respondent, and the most expensive consumable used for the analysis of the seawater sample batch along with its cost. Lastly, analogous questions were asked about the type of sampling equipment (e.g. manta net) the respondents would use to acquire these exact same samples (see Appendix A. Survey questionnaire). Within the survey, responses either had to be chosen from a list of options with the possibility of adding their own option (single-choice and multiple-choice depending on the question), or a slider bar response scale system was used where participants could indicate costs.

Data analysis

Unrealistic data, which were excluded from further analyses, were defined as: 1) median gross annual salaries higher than double and lower than half the mean wage of the respondents' country of employment [18]; 2) sample processing working hours over five times lower or higher than the obtained median processing working hours; 3) sample analysis working hours over six times lower or higher than the obtained median analysis working hours; 4) sample processing equipment costs over or lower than eight times the obtained median cost; and sample analysis equipment costs over four times lower or higher than the obtained median cost. Following this, all standardised data was classified into different analysis technique categories based on the most expensive type of analysis equipment used by a respondent.

a) Labour and equipment cost calculations

To calculate the total cost associated with the analysis of one batch of five seawater samples based on equipment usage intensity, sample processing labour and equipment costs as well as sample analysis labour and equipment costs were considered. This was done using the following formulas:

$$Labour\ cost\ = \frac{median\ man\ hours\ *\ gross\ annual\ salary}{man\ hours\ per\ year} - \tag{1}$$

$$Equipment\ cost = \frac{\frac{median\ equipment\ purchase\ price}{equipment\ depreciation\ time\ -\ salvage\ value}}{\frac{number\ of\ analysed\ batches}{year}} \tag{2}$$

$$\begin{aligned} Total\ cost\ =\ & sample\ processing\ labour\ cost \\ & +\ sample\ processing\ equipment\ cost \\ & +\ sample\ analysis\ labour\ cost \\ & +\ sample\ analysis\ equipment\ cost \end{aligned} \tag{3}$$

Labour (1) and equipment (2) costs were calculated for the sample processing and the analysis part of each of the six major analysis technique categories in the country of employment of the respondents (see Table S1 and S2), to determine the total cost (3). For the labour costs, median man hours needed to perform each of the two workflow steps were calculated for each of the six major analysis techniques categories based on 1634 working hours per year (for calculation details, see Methods Supplement: Labour and equipment cost calculations). Three different simulations were performed based on the gross national income per capita (GNI p.c.) of the countries of employment of the respondents, which is a country's final income in a year divided by the midyear population. To do so, GNI p.c. data from the World Bank were used [73]. Wage data of respondents employed in Estonia, Poland, Portugal, Spain and Romania were grouped within the *lower wage (LW) European countries* category (GNI p.c. below 29,620 EUR, calculated at exchange rate of 1 USD = 0.82 EUR on 1/01/2021 through www.xe.com); wage data of respondents employed in Belgium, Finland, France, Germany, Italy, Sweden and UK were grouped within the *middle wage (MW) European countries* category (GNI p.c. between 29,620 and 52,681 EUR); and finally wage data of respondents employed in Denmark, Ireland and Norway were grouped within the *higher wage (HW) European countries* category (GNI p.c. above 52,681 EUR). As the majority of respondents indicated that sampling did not come with additional

equipment purchase costs, and since ship time costs can vary considerably depending on government coverage, it was decided not to incorporate sampling costs into the equation.

b) Total sample analysis cost as a function of equipment usage intensity

The depreciated cost of used equipment was determined, which is the equipment value after reducing its value when it was new by the total amount of depreciation. The yearly decrease in monetary value of equipment due to use, wear and tear, or obsolescence was calculated at a 20% depreciation rate, which equalled a total use of five years, and this for both sample processing and sample analysis equipment. For the estimated equipment book value after the depreciation is completed, a salvage value of 0 EUR was used [47]. The depreciated equipment cost was calculated by subtracting its salvage value (i.e. 0 EUR) from the purchase cost, and dividing it by the number of years of useful life (i.e. five years). To determine the depreciated equipment cost as a function of equipment usage intensity, the total depreciated equipment cost was divided by the number of analysed sample batches/year, as defined earlier. Calculations were done for a range of 10 to 200 batch analyses/year. Total microplastic analysis cost, i.e. the sum of all labour and equipment costs, was then plotted as a function of equipment usage intensity for each of the six analysis technique categories, and this for each of the three income groups. Between 10 and 50 batches/year is indicated as low, between 50 and 100 as medium and 100–200 as high equipment usage intensity.

c) Workshops

Two iterative workshops were designed to present, discuss, and build a consensus around cost-effective microplastic analysis methodologies for seawater sampling. Both workshops were held online using Zoom and applied the same workshop structure and participatory method, which are detailed in the associated workshop reports [31, 32]. A guided conversation was adapted and applied for both workshops, in which a series of questions were presented to workshop participants to encourage reflection on the presented work and to make recommendations that support informed decision making and consider cost-effectiveness of sampling, processing, and analysis of microplastic seawater samples. Workshop 1 was implemented with researchers and scientists working in the same field with the aim to validate preliminary analysis outcomes with scientific experts, to discuss the potential applicability of our cost-effectiveness analysis for research and make recommendations concerning future research. Ten researchers and scientists representing eleven organisations from across eight European countries participated.

ANDROMEDA partners from MaREI at University College Cork (Ireland), VLIZ—the Flanders Marine Institute (Belgium) and ILVO—the Flanders Research Institute for Agriculture, Fisheries and Food (Belgium) identified potential participant organisations for workshop 2 based on the remit of organisations and entities, while being mindful to invite representatives of organisations that could provide complementary perspectives. The team was primarily looking to engage representatives of entities that are responsible for informing or implementing coastal and marine policy, are tasked with monitoring the marine environment, or provide research funding for coastal and marine research. Invited participants represented organisations ranging from pan-European entities to National agencies. Workshop 2 was undertaken with eight policy experts and decision makers representing OSPAR, the JPI Oceans secretariat, the Joint Research Centre (JRC), the Royal Belgian Institute of Natural Sciences (RBINS), the Belgian Federal Science Policy Office (BELSPO), the Flanders Marine Institute (VLIZ), the Marine Institute in Ireland (MI), the Marine Environment Division of the Department of Housing, Local Government and Heritage in Ireland and the UK Centre for Environment, Fisheries and Aquaculture Science (CEFAS). Workshop 2 included a summary presentation of Workshop 1 recommendations to allow for further reflection and discussion and aimed to make recommendations on the potential applicability of our CEA in environmental monitoring and in relation to environmental policy and regulations.

d) Method effectiveness scoring

Following suggestions made by policy experts and decision makers during workshop 2, a method-effectiveness scoring system was established to determine the effectiveness of each of the six analysis technique categories (Table 1). The criteria were selected based on received suggestions and on previously used analytical method assessment criteria [24, 39, 53, 54], and were based on the abilities/characteristics of the six identified method categories. The criteria used were the following: 1. Confirmative plastic/non-plastic; 2. Physical characterisation of microplastics (number/size/shape); 3. Microplastic mass determination; 4. Polymer identification; 5. Limit of Detection (LOD) > 300 µm (0), > 50 µm (1) or < 50 µm (2); 6. Characterisation of particles that are challenging to detect, such as tire wear particles (TWP); 7. Whether or not the method is destructive for the analysed sample, and 8. Identification of chemical additives.

Table 1 Method-effectiveness scoring system. A method-effectiveness scoring system based on eight criteria in terms of method abilities/characteristics was established for all analysis methods used by the respondents. This was accomplished based on suggestions made by policy experts and decision makers during workshop 2

Method	Method subcategory	Confirmative plastic/non-plastic	Physical character-isation MPs	MP mass determination	MP polymer identifi-cation	LOD > 300 µm (0), > 50 µm (1) or < 50 µm (2)	TWP character-isation	Identifi-cation of chemical additives	Destructive for sample	Total score
(Fluorescence) (Stereo) microscopy	Microscopy	0	2	1	0	2	0	0	2	**7**
	Stereomicroscopy	0	2	1	0	1	0	0	2	**6**
	Fluorescence microscopy	0	2	1	1	2	0	0	2	**8**
	Fluorescence stereomicros-copy	0	2	1	1	1	0	0	2	**7**
(Stereo)microscopy + ATR-FTIR		2	2	1	2	0	1	0	2	**10**
(Stereo)microscopy + µ-FTIR	Microscopy	2	2	1	2	2	1	0	2	**12**
	Stereomicroscopy	2	2	1	2	1	1	0	2	**11**
Fluorescence (stereo) microscopy + µ-FTIR	Fluorescence microscopy	2	2	1	2	2	1	0	2	**12**
	Fluorescence stereomicros-copy	2	2	1	2	1	1	0	2	**11**
(Stereo)microscopy + µ-Raman	Microscopy	2	2	1	2	2	1	0	2	**12**
	Stereomicroscopy	2	2	1	2	1	1	0	2	**11**
GC–MS-based techniques		2	1	2	2	2	2	2	0	**13**

The scoring system used was based on [26]. Scores ranged from 0 to 2, where 0 indicated that the method does not have this ability, 2 indicated that all methods within this category have this ability, while 1 indicated that only some methods have this ability. For criterion 5, a method with LOD > 300 µm, > 50 µm or < 50 µm was given a score of 0, 1 or 2, respectively. For criterion 7, a score of 2 or 0 was given to non-destructive or destructive methods, respectively. Finally, with regard to criterion 8, methods that could identify at least one type of chemical additive received a score of 2, whereas methods that could not provide any information on chemical additives were assigned a score of 0. Once each criterion was scored, an overall effectiveness score was calculated as the product of all criteria scores, resulting in a maximum theoretically obtainable score of 16, indicating a high method-effectiveness.

Results

The survey was completed by respondents from 15 different European countries, and the UK. The majority of the participants were senior scientists and PhD students (Fig. S2 and S3). Based on the standardised data, the most popular microplastic sampling equipment was manta nets (45%), followed by pump and sieve systems (21%), neuston nets (14%) and niskin bottles (14%). Plankton and bongo nets were less frequently chosen (both 3%) (Fig. 1A). In accordance with the standardised data, six different analysis technique categories were created (Fig. 1B and Table S1): 1. (fluorescence) (stereo)microscopy, comprising all purely microscopy-based techniques; 2. (stereo)microscopy combined with ATR-FTIR; 3. (stereo)microscopy combined with µ-FTIR; 4. fluorescence (stereo)microscopy combined with µ-FTIR; 5. (stereo)microscopy combined with µ-Raman; and 6. all GC–MS-based techniques. For details on labour hours/costs and equipment costs, see Figs. S4 and S5, and Table S2.

Total sample analysis cost as a function of equipment usage intensity

To simulate total sample analysis cost, i.e. the sum of all labour and equipment costs, as a function of the intensity with which the equipment is being used, three graphs per wage category are presented (see Fig. 2 for MW European countries, Fig. S6 and Fig. S7 for LW and HW European countries, and Annex A for the predictive tools). As can be seen in Fig. 2, at an equipment usage intensity of 10 batches/year for MW countries, analysis costs vary greatly depending on the method used. For this scenario, the most expensive method is over 10 times more expensive than the most economic method: the highest total cost was obtained for GC–MS-based techniques (8433 EUR), followed by fluorescence (stereo)microscopy + µ-FTIR (4073 EUR), (stereo)microscopy + µ-Raman (3810 EUR), (stereo) microscopy + µ-FTIR (3485 EUR), (stereo)microscopy + ATR-FTIR (1431 EUR) and purely microscopy-based techniques (792 EUR). When equipment usage intensity increases to 50 batches/year for MW European countries, this difference in total cost decreases. Methods with a high equipment purchase cost show a steep decline in costs. For example, for methods based on GC–MS and on fluorescence (stereo)microscopy + µ-FTIR, total cost per batch is reduced to 1987 EUR (-76%) and 1233 EUR (-70%), respectively, while for purely microscopy-based techniques, total cost decreases to 443 EUR (-44%). (Stereo)microscopy + µ-FTIR becomes more expensive (1270 EUR) than (stereo)microscopy + µ-Raman (1262 EUR) from an equipment usage intensity over 30 batches/year onwards. At an equipment usage intensity of 65 batches/year, methods utilising fluorescence (stereo)microscopy + µ-FTIR become

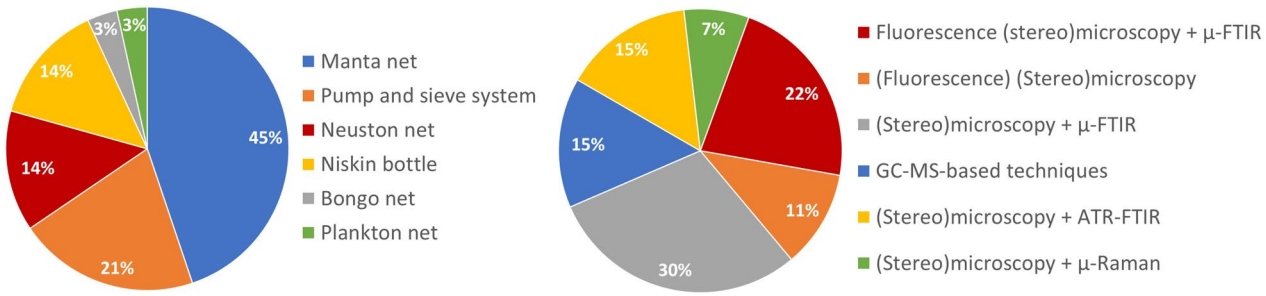

Fig. 1 **A** and **B** Microplastic sampling and analysis techniques. **A** According to the obtained data, the most popular sampling equipment to acquire microplastic samples was manta nets (45%), followed by pump and sieve systems (21%), neuston nets (14%), niskin bottles (14%), and plankton and bongo nets (both 3%). **B** Based on the standardised data, six different analysis technique categories were created. Of all respondents, 30% used techniques based on (stereo)microscopy + µ-FTIR, 22% on fluorescence (stereo)microscopy + µ-FTIR, 15% on (stereo) microscopy + ATR-FTIR, 15% on GC–MS, 11% on (fluorescence)(stereo)microscopy, and 7% on (stereo)microscopy + µ-Raman

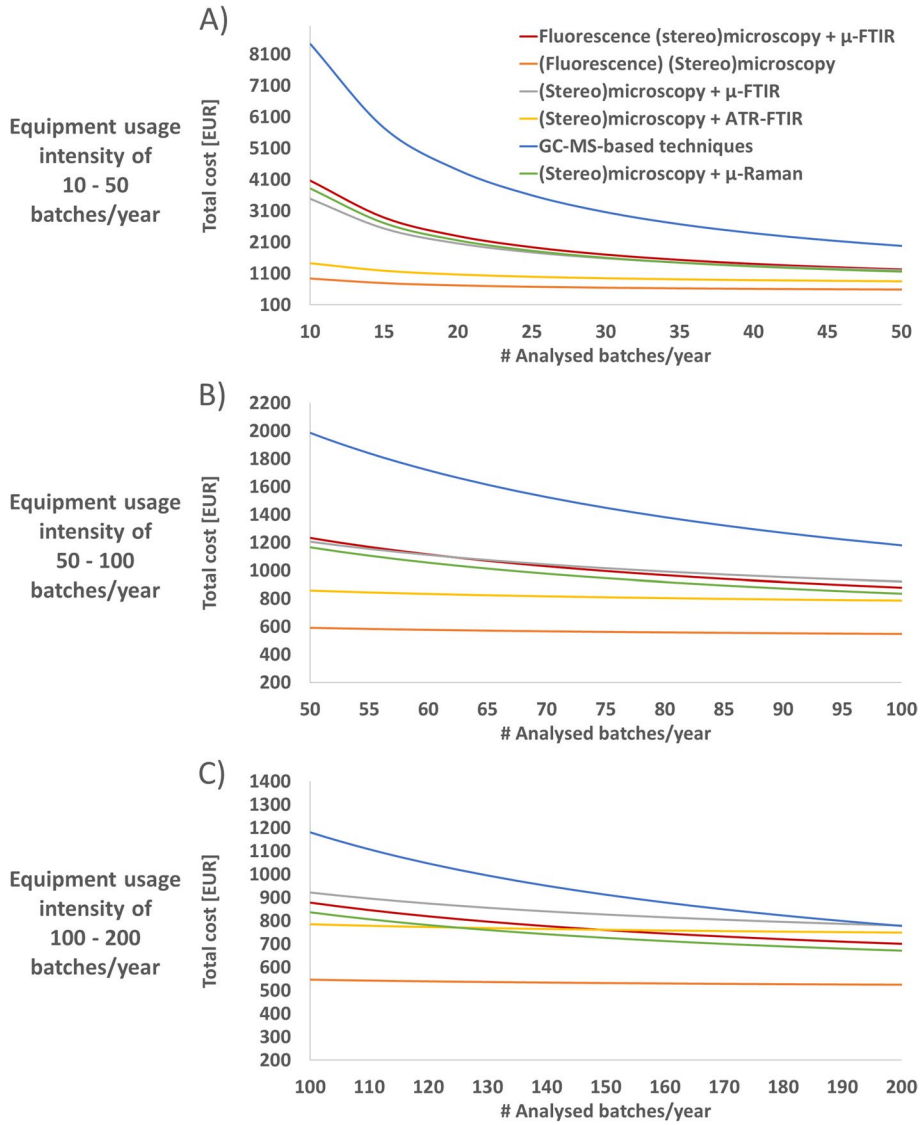

Fig. 2 **A**, **B** and **C** Total sample cost as a function of the equipment usage intensity for middle wage European countries. Total sample analysis cost can be deduced as a function of the number of analysed batches of five seawater samples per year (equipment usage intensity), and this for each of the six method categories. On the graph in **A**, total cost for a low equipment usage intensity of 10–50 batches/year is shown, on the graph in **B** total cost for a middle equipment usage intensity of 50–100 batches/year, and for the graph in **C** total cost for a high equipment usage intensity of 100–200 batches/year. These graphs represent costs for European countries with a gross national income per capita (GNI p.c.) between 29,620 EUR and 52,681 EUR, as defined by the World Bank

more economically appealing (1069 EUR) compared to those based on (stereo)microscopy + µ-FTIR (1075 EUR). With intensive equipment usage (200 batches/year), all methods range between 693 and 780 EUR in total cost, except for purely microscopy-based methods (378 EUR). At this intensity, (stereo)microscopy + µ-FTIR becomes the most expensive method (780 EUR), marginally surpassing GC–MS-based methods (778 EUR), while methods based on fluorescence (stereo)microscopy + µ-FTIR (701 EUR) as well as on (stereo)microscopy + µ-Raman (671 EUR) outperform methods based on (stereo) microscopy + ATR-FTIR (778 EUR). Besides higher or lower total costs due to varying labour costs (e.g. 3885 EUR; 4290 EUR; and 4073 EUR for fluorescence (stereo) microscopy + µ-FTIR-based methods at an equipment usage intensity of 10 batches/year for LW, HW and MW countries, respectively), location-dependent differences in cost-effectiveness become visible when comparing the results for MW countries to those for LW (Fig. S6) and HW countries (Fig. S7). For instance, for HW countries,

(stereo)microscopy + μ-Raman becomes more economical than (stereo)microscopy + μ-FTIR from an equipment usage intensity of 25 batches/year onwards. For LW countries, this only happens at an equipment usage intensity of 60 batches/year onwards. Similarly, fluorescence (stereo)microscopy + μ-FTIR become more economically interesting than (stereo)microscopy + μ-FTIR already from an equipment usage intensity of 45 batches/year onwards for HW countries, while for LW countries this happens from an equipment usage intensity of 100 batches/year onwards. Moreover, in HW countries, from an equipment usage intensity of 145–155 batches/year onwards, GC–MS-based methods become more economically appealing than both methods based on (stereo) microscopy + μ-FTIR and on (stereo)microscopy + ATR-FTIR. GC–MS-based methods become the most economical method available that is confirmative for plastic at an equipment usage intensity of 220–225 batches/year (see Annex A), because of the relatively low working time, and consequently labour costs. In contrast, this method remains the most expensive method for LW countries until an equipment usage intensity as high as 310 batches/year, where it surpasses (stereo)microscopy + μ-FTIR-based methods. Compared to HW countries, the impact of labour costs on the total cost is less pronounced here.

Method effectiveness

Effectiveness scores were given to each of the six analysis categories based on the abilities of each of these techniques, with scores theoretically ranging between 0 and 16 (Table 1). Compared to all other methods, GC–MS-based methods obtained the highest score of 13. This is mainly due to their ability to identify tire wear particles [22, 43, 57], unlike other methods. However, physical characterisation of microplastics cannot be performed with a technique solely based on GC–MS analysis, therefore information on microplastic number, size and shape can only be obtained when an additional μ-FTIR analysis of a (sub)sample of microplastics is performed. Effectiveness scores for (stereo)microscopy + μ-Raman ranged between 11 and 12. The major difference between both categories is the use of a stereomicroscope with LOD > 50 μm, and microscope with LOD < 50 μm, respectively. The analysis categories (stereo)microscopy + μ-FTIR and fluorescence (stereo) microscopy + μ-FTIR also received effectiveness scores ranging between 11 and 12, again depending on what type of microscope is being used. Contrary to the previous category, techniques within these categories do give information on physical characterisation of microplastics, but mass determination cannot be performed with these methods without adding an additional weighing step to the analysis. Furthermore, TWP characterisation with these techniques is not straightforward [20]. (Stereo)microscopy + ATR-FTIR received a score of 10. The major difference of this category with (stereo) microscopy + μ-FTIR is its LOD, which received a score of 0 as ATR-FTIR cannot accurately analyse particles below 300 μm in size [70]. Lastly, (fluorescence) (stereo) microscopy received an effectiveness score of 6–8, which is lower than all earlier mentioned scores. One of the factors causing this lower score is the inability of these techniques to be confirmative for the plastic nature of a particle, as well as their inability in most cases to identify microplastic polymer type. Lastly, as with all of the aforementioned microscopy-based techniques, LOD depends on the microscope type.

Workshops

Participants of both ANDROMEDA workshops concluded that the presented preliminary results should be published to allow for repetition and adaptation of the approach. Adaptation of the approach was discussed in relation to adding additional criteria and context, such as accounting for different microplastic size classes, incorporating environmental criteria and policy related fields. Discussions at both workshops highlighted the relevance of the approach to environmental monitoring programmes and the need to build on systems that are in place. However, monitoring featured more prominently in the discussions with the policy and decision makers, while the scientists and researchers focused more on the financial context in which the preliminary results were presented [31, 32]. The specific recommendations from both workshops are summarised in Table 2.

Discussion

Because of the diverse nature of microplastics in terms of their polymer composition and related densities, shape, size range, the additives present, and their ageing condition, identification of an appropriate microplastic analysis method is challenging [29]. The choice of method depends on the research objectives, and the matrix type considered, but is also influenced by the financial means available.

Equipment costs and working hours

Total cost for microplastic analysis is strongly determined by equipment and labour cost for both sample processing and analysis. For sample processing, a combination of filtration devices and pumps was most frequently applied by survey respondents. To ensure accurate reflections of these equipment cost calculations, the median of the total sample processing equipment cost was calculated for each of the six analysis

Table 2 Workshop recommendations. ANDROMEDA workshop recommendations summarised per participant group, which were scientists and researchers in Workshop 1 and policy and decision makers in Workshop 2

Scientist & Researcher	Policy & Decision Maker
Limitations of the research and data should be clearly stated to show that the work focuses on cost-effectiveness only, and that the quality of the method is not included in the survey. Additionally, the calculations are not general but pertain to a specific size of microplastics.	There needs to be a clear distinction between assessing methodologies and approaches focused on research and for monitoring when considering cost-effectiveness.
Monitoring	
Scientists need to actively engage with policy and decision-makers concerning the definition of what to measure for the purposes of government monitoring programmes, ensuring that the data being collected is put into perspective.	It is important to feed approaches on cost-efficiency into monitoring programmes that are comparable across the EU and what is used at a wider international level, so that an accepted and feasible approach for microplastics monitoring can emerge. Considerations should be given to what is currently being done. It will be necessary to determine the easiest way to examine trends.
Financial Context	
Affordability and cost-effectiveness should be considered in the context of gross national income (GNI) and gross domestic product (GDP).	Cost-effectiveness is of great importance in a monitoring framework and developed approaches must be accessible to and feasible for all Member States and contracting parties.
Future Research	
Should incorporate environmental factors, such as seasonal disruption and the organic matter content of samples, to obtain a more detailed picture of costs that occur for different size classes.	Should incorporate other criteria that are important for monitoring and environmental parameters that are mandatory and link to source emissions for microplastics.
Should consider costs based on the findings of inter-collaboration studies between institutes that apply different methodologies and techniques but get comparable results.	Should consider a repetition of a similar survey that includes a wider stakeholder community with focus on policy needs, harmonisation, and what is feasible for all.
Include calculations that use less expensive equipment or protocols and adjust for different batch level sizes.	Should reflect on how to develop approaches that can support the European Commission's Zero Pollution Ambition and associated environmental monitoring requirements.

techniques individually. Sample analysis equipment is in general more expensive than equipment used for sample processing, and can be a significant investment for research laboratories. For example, the use of GC–MS-based techniques requires purchasing equipment that can cost over 500,000 EUR, while 16,000 EUR can be sufficient to buy the equipment for (fluorescence) (stereo)microscopy-based techniques (Table S2). Within an analysis technique category, equipment purchase costs can also vary greatly, e.g. when buying new vs. second-hand equipment. Furthermore, laboratories may opt to invest in a more versatile and advanced model of a specific instrument, which has additional capabilities beyond the requirements for microplastic analysis. Despite higher costs, this decision allows equipment to serve multiple research purposes, accommodating the needs of various research groups including those that are not focused on microplastics.

Not all costs associated with the different techniques were incorporated in the calculations. An example is equipment maintenance costs, which can vary between methods (e.g. microscopes vs. GC–MS). Furthermore, microplastic analysis faces challenges in estimating consumable costs due to variations in required materials depending on specific techniques and experimental conditions. The diversity of the most expensive consumable used per technique, such as filters, solvents, and reagents (Fig. S8), makes it difficult to generalise cost estimates across all methods.

Sample processing time varies between and within different technique categories depending on the analysis equipment and its sample preparation requirements. In most cases, if organic material is present in the samples, regardless of the method used, an alkaline, oxidative or enzymatic digestion is performed before filtration [28, 37, 51]. The duration of this cleaning step depends on the type, intensity and number of consecutive treatments, which in turn is determined by the amount of organic material present as well as the analysis equipment requirements of a specific method. For instance, for certain methods effective removal of organic material present may be more crucial than for others, therefore a double digestion step may be favoured over a single step. In the case of e.g. (fluorescence) (stereo)microscopy-based methods, this helps prevent co-staining of organic residue and consequently overestimation of the microplastic content [3, 74]. Seawater samples often contain SPM which can interfere with microplastic analysis. The degree of interference determines the necessity for a sediment removal step before filtration, as well as the thoroughness of the removal step. In most cases a density separation is performed to extract microplastics [67],

where the number of times this procedure is repeated determines processing time, as well as the microplastic recovery of a sample.

For all techniques, the number of working hours needed for sample analysis were larger than that for sample processing. Sample analysis working hours varied greatly between analysis methods as well as within method categories. An important factor influencing this is the degree of automation of such a method. The results of the survey and the workshop discussions clearly demonstrated the benefits of automation for microscopy- based techniques (e.g. for fluorescence (stereo) microscopy + μ-FTIR) in reducing the analysis time for the operator, and hence the labour costs. Manual counting and sorting of microplastics and additional polymer identification are time-consuming processes. Moreover, such methods are prone to human error. Researchers have attempted to lower microplastic characterisation costs and remove human bias by automating (parts of) microplastic analysis. Purely microscopy-based techniques have been automated for microplastic analysis purposes in various studies (e.g. [41, 52]), with a shown reduction in analysis time. Spectroscopic techniques, such as FTIR spectroscopy are one of the most widely applied techniques for the identification of microplastics. Traditional FTIR-analysis where samples are first visually screened for microplastics using a microscope, followed by spectroscopic analysis of each particle individually is very labour-intensive. For example, for ATR-FTIR ((stereo)microscopy + ATR-FTIR), even though microplastic analysis itself is quite straightforward with no extensive sample preparation, fixing the ATR-crystal on the particles surface to obtain IR data is time-consuming when many particles need to be analysed. An FTIR or Raman spectrometer used in conjunction with an optical microscope are referred to as μ-FTIR (fluorescence (stereo) microscopy + μ-FTIR and (stereo)microscopy + μ-FTIR) or μ-Raman ((stereo)microscopy + μ-Raman). Both methods are particle-based methods that can be carried out either through imaging or particle measurements. Automation here can save operator time by creating a high-throughput, programmed screening step which requires only to set up an area to scan or image, apply a threshold and start the automated analysis. Increasing the number of particles analysed here will require higher cost equipment and longer instrument running times, providing more results with reduced operator man hours and consequently labour costs.

Processing and evaluating the resulting spectra is another laborious analysis step, especially when dealing with large datasets and high particle variability, which can be expedited through automation. Machine learning processes such as auto-encoding neural networks can effectively process a broad variety of spectral types and at the same time minimise operator bias. However, although this approach is efficient, such networks need to be trained first and a correct match is not guaranteed. Development of reference libraries is often required, resulting in longer working hours and hence higher labour expenditure. Commercial libraries can be used instead, but these are often only available through paid subscriptions, which can be an expensive commitment [13]. Moreover, these methods are still being developed and currently not fully established or proven to be fully cost- and time-efficient. In the case of Focal Plane Array (FPA) μ-FTIR [55], for instance, it has been shown that automating the analysis process can still be time-consuming, which highlights the difficulties in attaining faster automated analysis. To address this issue, parallelisation of the process could be implemented by executing macros and scripts concurrently on multiple computers.

Likewise, data processing of GC–MS analysis results is a time-consuming step often done manually. Accelerating this process through automation is one of the challenges facing this technique nowadays [59]. However, in contrast to spectroscopy-based techniques, GC–MS-based techniques provide plastic polymer information of a sample in a single analytical run, which speeds up the analysis process. Here, particles do not need to be handled one by one, and enrichment of microplastic particles is only necessary if the mass content is below the LOD [8]. It should be stressed, nonetheless, that automation of any method workflow does not necessarily equal a cost-effective workflow [54].

Cost-effectiveness of microplastic analysis techniques as a function of equipment usage intensity

The cost-effectiveness of microplastic analysis methods for seawater samples is influenced by multiple factors, including the research questions, the equipment used and associated maintenance costs, the intensity at which the equipment is being used as well as its depreciation time, the degree of automation, the position and seniority of the executing employees as well as the required skills and potential additional training, the country of employment, and the consumables needed. Generally, the more frequently and intensively the equipment is used, the lower the cost per analysis. For laboratories conducting exploratory research on microplastics, the equipment usage intensity may be low. For instance, a batch of 5 samples every two weeks or every month would result in an equipment usage intensity of 12–26 batches/year. Here, equipment costs weigh in more on the total cost compared to labour costs. On the other hand, commercial labs that offer services to e.g. customers from industrial sectors or governmental/regulatory agencies often

perform routine analyses. In scenarios where 20 seawater samples per week need to be analysed for microplastics year-round using a GC–MS-based technique, the equipment usage intensity is 209 batches/year (*(20 samples per week)/(5 samples per batch)*52.14 weeks*). For such routine analyses, investment in high-cost equipment is quickly earned back, with costs at a higher equipment usage intensity mainly determined by the labour costs and hence the man hours needed.

When evaluating the cost-effectiveness and affordability of different methods, the gross domestic product (GDP) context, which represents the value of all final goods and services a country produces over a period of 1 year, as well as potential disparities across countries should be taken into consideration when developing transnational monitoring schemes. In HW European countries, labour costs have a larger influence on the total cost compared to that in LW European countries, especially at a high equipment usage intensity (see '3. Results', Table S2, and Annex A). As a consequence, differences in labour costs across countries will impact the cost-effectiveness of a method at a given equipment usage intensity. In this context, it is important to note that cost-effectiveness in relation to national income and GDP was a strong focus in Workshop 1 discussions with researchers and scientists. Workshop 1 participants specifically highlighted that initial investment may be required to allow for a change of methods or equipment towards more cost-effective approaches and that further study considering national income and GDP would be useful [31]. These discussions resulted in a specific recommendation on affordability and cost-effectiveness noted in Table 2 in the results section.

Method effectiveness

When selecting the most suitable microplastic analysis method, a comprehensive approach that encompasses not only costs but also method effectiveness is crucial. A first important reason to do so is the limited budgets research and monitoring programs often have. Allocating resources efficiently ensures that other important aspects of the study can also be adequately addressed without losing valuable information. Another vital reason is scalability. A cost-effective method allows for the analysis of a larger number of samples, encompassing various sample types, locations, and timeframes, and leading to more robust conclusions and recommendations. A third consideration is the quality and reliability of the data obtained. By selecting an effective method, researchers can ensure its sensitivity for the reliable detection and quantification of environmentally relevant microplastic concentrations, which is needed to draw meaningful conclusions on microplastic contamination levels. Furthermore, cost-effective methods can contribute to the development of accurate and affordable, standardised protocols, which in turn enables data harmonisation, facilitates collaborations, allows for comparison of results across different studies, and strengthens the overall scientific knowledge base. Lastly, excessively expensive methods may not be viable for routine monitoring or continuous assessment of microplastic pollution levels. By choosing a cost-effective method, researchers can promote the long-term sustainability of their work, thereby ensuring that monitoring efforts can be maintained over extended periods of time.

Depending on the objectives of the research, method requirements differ. The effectiveness of a method is therefore highly dependent on the aim of the research performed. For instance, research can be focused on mapping microplastic pollution, source identification, fate assessment or ecotoxicological evaluations, all with different requirements regarding microplastic characterisation and quantification. This can be in terms of their LOD and their ability to identify polymer types, their ability to provide information on microplastic size, shape and colour; and the units in which results are expressed, e.g. mass vs. count [64]. Many research questions can be addressed using microplastic count, such as identifying microplastic hotspots, assessing the efficiency of water treatment systems, performing microplastic risk assessments, and so on [6, 30]. On the other hand, microlitter indicator values for microplastic monitoring in the upper water layer are often reported in 'number of particles per m^3' but also in 'g per m^2' [40, 65]. The effectiveness of a method is therefore inherent to the research goal.

a) Microscopy-based techniques

In the realm of microplastic analysis techniques, (fluorescence) (stereo)microscopy-based techniques, while economical, show a low effectiveness. Their primary drawback lies in their inability to confirm the plastic nature of a particle, which can lead to potential underestimation or overestimation of microplastic presence in samples. Such inaccuracies can skew assessments of microplastic pollution, either by downplaying its severity or by prompting unnecessary regulatory measures. Identification relying solely on colour and morphology may result in error rates up to 70%, especially for smaller particles, undermining the accuracy of assessments [27, 33, 36]. Although certain microscopy methods can categorise microplastics into polymer classes [41], most of the techniques in this category do not have to ability to do so. As a consequence, the broader understanding of plastic types polluting specific areas as well as their sources remains elusive using this method.

Furthermore, the choice of microscope type is pivotal: while stereomicroscopes can detect microplastics down to around 50 µm, crucial particles under 20 µm which pose ecological risks ([9, 62], elude detection. Microscopes have a LOD below 50 µm, but require a longer working time due to their substantially smaller field of view compared to stereomicroscopes. Tire wear particles (TWP), generated through mechanical abrasion of tire materials, have been causing concern in recent times due to their prevalence in the environment, their persistence as well as their toxicity [34, 68]. Light microscopes offer a tentative quantification method for TWP based on physical and morphological properties [49], while fluorescence microscopy fails in this regard [16].

b) Microscopy combined with spectroscopy

(Fluorescence) (stereo)microscopy-based analyses are often complemented with vibrational spectroscopic methods such as IR absorption and Raman scattering, as these methods can confirm the plastic nature of a particle as well as its polymer type: (stereo)microscopy + ATR-FTIR, (stereo)microscopy + µ-FTIR, fluorescence (stereo)microscopy + µ-FTIR and (stereo) microscopy + µ-Raman. These methods allow for reporting the number of particles and to identify the degree of weathering. Moreover, they facilitate non-destructive analysis, preserving valuable samples, a crucial advantage when dealing with limited samples [2, 10, 58].

A drawback of ATR-FTIR-based methods is their large minimum detectable particle size (LOD). Particles should be at least 200—500 µm in size for proper identification and to avoid damaging the ATR-instrumentation due to analysis of inorganic particles resembling microplastics [29]. By focusing on just the larger particles, insights on microplastics of ecotoxicological relevant sizes are lost. µ-FTIR-based methods have a LOD of 10—20 µm, which is determined by their spatial resolution in infrared imaging [4, 53]. FTIR-based methods can provide information on microplastic size, shape and morphology, which is vital for understanding their impacts on marine life [56, 60]. Moreover, by characterising the size and shape of microplastics, researchers can identify their likely sources, information that is essential for targeted interventions and regulatory measures against plastic pollution. Stereomicroscopy aids visual microplastics identification but may introduce visual bias. Fluorescent staining with the fluorescent dye Nile red [38], combined with fluorescence microscopy, enhances microplastic detection, although caution should be taken as co-staining of undigested organic material may happen and microplastic content may be overestimated [63]. The simplified identification of fluorescently stained microplastics reduces time and effort required for manual microscopic analysis prior to spectroscopic analysis, which may explain the lower working time (Fig. 2). Moreover, automating the analysis procedure using image analysis softwares like ImageJ [69] allows for a high-throughput screening with subsequent (automated) chemical analysis, which further streamlines the analysis process, thereby providing a more efficient and cost-effective solution. TWP analysis using FTIR-based methods is however intricate [35] due to the similarity in composition of their components, as well as the necessity to prepare particles in a form suitable for FTIR-analysis [57]. Lastly, mass determination cannot be performed with FTIR-based methods without an additional weighing step. For small particles, this parameter can only be approximately calculated by processing analysis data in programs like siMPle [55].

Raman spectroscopy, while able to reliably detect and identify microplastics down to 1 µm, faces challenges with fluorescence interference, both intrinsic to the particle or following staining with a dye like Nile red [4]. Prescreening of particles without selective fluorescent staining may consequently slow down the analysis of environmental samples containing a lot of non-plastic materials. Moreover, Raman spectroscopy is unsuitable for the analysis of black TWP as they do not provide a specific spectrum [71].

c) GC–MS-based techniques

GC–MS-based techniques are able to detect microplastics and are capable of determining the polymer types present in a sample. Unlike all previously mentioned methods, GC–MS is adept at quantifying TWP, MP-associated additives, and microplastic degradation byproducts as a consequence of environmental weathering, of which some were found to be toxic, carcinogenic, or disrupting of the endocrine system [19, 61]. Data produced by these techniques is consequently valuable for assessing microplastic risks in marine ecosystems and for human health. Unlike spectroscopy, GC–MS is not influenced by physical characteristics, offering a distinct advantage. The technique provides precise mass-based concentrations, typically down to 0.008—0.22 µg/mg, without size limitations [8, 29, 48]. However, a major disadvantage is the lack in ability to physically characterize microplastics and report particle numbers, which is essential for comprehensive risk assessments. To obtain information on physical attributes, complementary spectroscopy-based analyses are needed. However, as GC–MS-based techniques are destructive with complete loss of sample as a result, subsequent particle analysis of that same sample is impossible.

Survey limitations

While the survey has its strengths in providing comparable results and highlighting positive aspects, there are certain limitations that need to be acknowledged. One such limitation is the use of a fixed number of samples and microplastic content for analysis, which, while ensuring method comparability and result consistency, restricts exploration of lower size limits in certain techniques. Additional costs, e.g. for consumables and maintenance, were also not included, as it is very challenging to generalise these costs across all methods. Furthermore, the presence of quality assessment criteria, like positive and negative controls, could have offered additional valuable insights on the different methods used. Besides this, the survey does not directly assess method performance or reproducibility, but integrating the survey into a ring test or comparative study could address this in the future. Lastly, the survey primarily engaged microplastic experts employed in European countries, reflecting a specific regional context. The absence of perspectives from researchers employed in other non-European countries represents a restriction of this study. In future research, a more diverse participant pool with variable socioeconomic backgrounds could offer a broader perspective on the cost-effectiveness of microplastic analysis methods by considering varying contexts as well as resource availabilities. Despite these constraints, the survey offers valuable insights and comparisons, emphasising its positive aspects.

Workshop recommendations

The predictive tools (see Annex A) developed in this study may have significant implications for monitoring efforts and the implementation of the Marine Strategy Framework Directive (MSFD), which was recognised by participants in both ANDROMEDA workshops and resulted in specific recommendations concerning environmental monitoring programmes outlined in Table 2. Table 2 highlights that cost-effectiveness is a significant consideration in environmental monitoring programmes (see monitoring and financial context section in Table 2), which featured greatly in discussion with the policy and decision makers in Workshop 2 [32].

Our CEA tool allows for the prediction of microplastic analysis techniques cost-effectiveness in the marine environment, providing valuable information for monitoring programs. Workshop discussion with scientists and researchers highlighted that it is important to apply approaches such as our CEA tool to the monitoring systems that are already in place to help identify where and how to adapt and improve existing systems [31], which was reinforced by policy and decision makers in Workshop 2, emphasising the importance to align development of our approach with OSPAR activities and MSFD requirements [32].

Furthermore, the tools can be used to allow for more informed decision-making regarding policy and management. The MSFD requires EU member states to achieve or maintain good environmental status in their marine waters by 2020, including a reduction in marine litter, including microplastics. The predictive tools can help member states to assess progress towards this goal by providing a more comprehensive understanding of the costs and techniques used to evaluate distribution of microplastic pollution. Policy and decision makers [32], emphasised that the developed tools could help to inform changes in monitoring that may need to be applied to a European-wide scale. Participants suggested the development of a knowledge base using the predictive tools to help evaluate different available technologies and methodologies according to cost and what needs to be detected, to inform the selection of appropriate and feasible technologies and methodologies [32].

Policy and decision makers made a number of suggestions how our CEA tools could be used and adapted in a policy and monitoring context, which relate to the reproducibility of the methodology, strengths and limitations related to microplastic detection, links to source emission measures, size limitation needed for monitoring, availability of technology in commercial labs, harmonisation of existing monitoring programmes within and outside of the EU, usability for other matrices (wastewater, industrial emissions, etc.) and contribution to filling current knowledge gaps, e.g. in relation to nanoplastics or risks [32]. Overall, the predictive tool developed in this study represents an important step towards a more effective and informed approach to monitoring and managing microplastic pollution in the marine environment, supporting the implementation of the MSFD and ultimately contributing to the protection of marine ecosystems and human health.

The potential for future application of an adapted CEA tool featured prominently in both ANDROMEDA workshop discussions, where participants emphasised the importance of the developed approach and made practical suggestions of areas that they would like to see further explored [31, 32], some of which have been outlined in the above discussion paragraph focused on links to environmental monitoring programmes and the MSFD. Other areas explored in workshop participants' discussion include adaptation of the CEA approach to reuse of available data, to other matrices such as sediment or fish [32], and to varying concentrations of organic material present.

Based on the explorative workshop discussions, participants made recommendations for future research

that should be considered to allow for informed and useful adaptations of the tool, which are outlined in Table 2. In this context, it is important to note the Workshop 2 participants' general recommendation to clearly distinguish between cost-effectiveness assessment of approaches that are research focused and approaches for monitoring requirements, which also needs to be considered in terms of future research aim and purpose. Overall, future research recommendations made by both workshop participant groups emphasise that the developed tool can and should be adapted, with both groups recommending the development and implementation of more surveys that are adapted to include additional criteria. Furthermore, scientist and researcher participants' general recommendations in Workshop 1 (see Table 2) also include specific emphasises on clearly stating the limitation of the presented research, data and approach.

Conclusion

The multitude of available microplastic analysis methods for comparable objectives makes it difficult for researchers to select the best method for their research question and a particular budget. In this study, survey data gathered from microplastic experts was used to conduct a cost-effectiveness analysis of methodologies for microplastic analysis in seawater. The overall analysis cost for each approach was determined including estimates of labour and equipment costs, while method features were used to estimate effectiveness using set criteria. This evaluation was then presented at two iterative workshops with researchers and scientists, and policy experts and decision makers, to validate the obtained results, and to share insights, perspectives and ideas related to the performed analysis.

Based on the GNI p.c. of the respondents' countries of employment, predictive tools were produced that allow the identification of the most cost-effective methods for specific scenarios, and to calculate the total analysis cost of each method. This indicated differences in the cost-effectiveness of the discussed methods depending on a variety of factors, including the country of employment. The workshops resulted in specific recommendations concerning environmental monitoring programmes, and highlighted that cost-effectiveness is a significant consideration. The developed and validated tools mark an important step toward a more effective and informed approach to monitoring microplastic pollution in the marine environment, and decision-making regarding policy and management. In this way, they support the implementation of the MSFD, and eventually help safeguard the marine environment and public health. Recommendations given by workshop participants for future research included flexibility of the predictive tool for the reuse of existing data, flexibility to assess methods used for additional marine matrices with varying concentrations of organic material, and flexibility through the implementation of more surveys. This would allow a detailed grasp of the costs and effectiveness of methods related to evaluating microplastic contamination throughout the marine ecosystems.

Abbreviations

EU	European Union
MSFD	Marine Strategy Framework Directive
CEA	Cost-effectiveness Analysis
LOD	Limit of Detection
GDPR	General Data Protection Regulation
WGML	Working Group on Marine Litter
SPM	Suspended Particulate Matter
GNI p.c.	Gross National Income per capita
LW	Lower wage
MW	Middle wage
HW	Higher wage
TWP	Tire Wear Particles
FPA	Focal Plane Array
GDP	Gross Domestic Product

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43591-024-00081-x.

Additional file 1: Appendix A. Survey questionnaire. **Methods Supplement.** Labour and equipment cost calculations. **Fig. S1.** Sample acquisition. **Fig. S2.** Respondents' country of employment. **Fig. S3.** Respondents' employment position. **Fig. S4.** Sample processing and analysis working hours. **Fig. S5.** Sample processing and analysis equipment costs. **Fig. S6.** Total sample analysis cost as a function of equipment usage intensity for LW (European) countries. **Fig. S7.** Total sample analysis cost as a function of equipment usage intensity for HW (European) countries. **Fig. S8.** Most expensive type of consumable used. **Table S1.** Analysis technique classification. **Table S2.** Equipment purchase and labour costs for sample processing and analysis.

Acknowledgements

The authors would like to thank Andy Booth, Ivo Int-Veen, Valter Castelvetro, João Frias, Michael Grelaud, Silvia Fraissinet, Win Cowger, Alexandra Savuca, and all other survey respondents who took the time to fill out the questionnaire and provide additional feedback. Furthermore, the authors would also like to express their gratitude to all facilitators who contributed their knowledge and expertise during the two workshops, and to all participants who generously shared their insights, perspectives and ideas related to the performed cost-effectiveness analysis. The international Atomic Energy Agency is grateful to the Government of the Principality of Monaco for the support provided to its IAEA Marine Environment Laboratories.

Authors' contributions

NM: Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualisation, Writing – original draft, Writing – review & editing. KK: Conceptualisation, Methodology, Investigation, Funding acquisition, Writing – original draft, Writing – review & editing. GE: Conceptualisation, Methodology, Project administration, Supervision, Funding acquisition, Writing – review & editing. NB: Conceptualisation, Methodology, Writing – original draft, Writing – review & editing. KM: Conceptualisation, Methodology, Writing – original draft, Writing – review & editing. CJ: Supervision, Funding acquisition, Writing – review & editing. BDW: Conceptualisation, Methodology, Project administration, Supervision, Funding acquisition, Writing – review & editing.

Funding
This work has been undertaken as part of the Andromeda project, which is funded by JPI Oceans. The work was specifically supported with funding from the Belgian Federal Science Policy Office (BELSPO) [contract no B2/20E/P1/Andromeda], the Pluxin project, the Marine Institute in Ireland and the Department of Housing, Planning and Local Government (DHPLG) in Ireland [contract no PBA/PL/20/01/ANDROMEDA], the Ministry of the Environment of the Estonian Republic (MoE) and the Estonian Research Council (ETag); and the Swedish Research Council (FORMAS).

Availability of data and materials
The predictive tools (Annex A) and data generated during the current study are available here: https://doi.org/https://doi.org/10.14284/636.

Declarations

Ethics approval and consent to participate
The survey participants provided their written informed consent to participate in this study.

Competing interests
The authors declare no competing interests.

Received: 19 November 2023 Accepted: 5 January 2024
Published online: 10 February 2024

References

1. Adhikari S, Kelkar V, Kumar R, Halden RU. Methods and challenges in the detection of microplastics and nanoplastics: a mini-review. Polym Int. 2022;71(5):543–51.
2. Akhbarizadeh R, Dobaradaran S, Torkmahalleh MA, Saeedi R, Aibaghi R, Ghasemi FF. Suspended fine particulate matter (PM2 5), microplastics (MPs), and polycyclic aromatic hydrocarbons (PAHs) in air: their possible relationships and health implications. Environ Res. 2020;192:110339. https://doi.org/10.1016/j.envres.2020.110339.
3. Al-Azzawi MSM, Kunaschk M, Mraz K, Freier KP, Knoop O, Drewes JE. Digest, stain and bleach: Three steps to achieving rapid microplastic fluorescence analysis in wastewater samples. Sci Total Environ. 2023;863:160947.
4. Araujo CF, Nolasco MM, Ribeiro AMP, Ribeiro-Claro PJA. Identification of microplastics using Raman spectroscopy: latest developments and future prospects. Water Res. 2018;142:426–40. https://doi.org/10.1016/j.watres.2018.05.060.
5. Arthur C, Baker J.E, Bamford H.A. Proceedings of the International Research Workshop on the Occurrence, Effects, and Fate of Microplastic Marine Debris, September 9–11, 2008. Tacoma, WA, USA: University of Washington Tacoma; 2009.
6. Ayankunle AY, Buhhalko N, Pachel K, Lember E, Kõrgmaa V, Mishra A, Lind K. Estimating Microplastics related to Laundry Wash and Personal Care Products released to Wastewater in Major Estonian Cities: a comparison of calculated and measured microplastics. J Environ Health Sci Eng. 2023;21(1):225–37. https://doi.org/10.1007/s40201-023-00856-z.
7. Barrett, J., Chase, Z., Zhang, J., Holl, M.M.B., Willis, K., Williams, A., Hardesty, B.D., Wilcox, C. 2020. Microplastic Pollution in Deep-Sea Sediments From the Great Australian Bight. Front. Mar. Sci. https://doi.org/10.3389/fmars.2020.576170
8. Becker R, Altmann K, Sommerfeld T, Braun U. Quantification of microplastics in a freshwater suspended organic matter using different thermoanalytical methods – outcome of an interlaboratory comparison. J Anal Appl Pyrol. 2020;148:104829. https://doi.org/10.1016/j.jaap.2020.104829.
9. Beiras R, Schönemann AM. Currently monitored microplastics pose negligible ecological risk to the global ocean. Scientific reports. 2020;10(1):22281.
10. Birch QT, Potter PM, Pinto PX, Dionysiou DD, Al-Abed SR. Isotope ratio mass spectrometry and spectroscopic techniques for microplastics characterization. Talanta. 2020;224:121743. https://doi.org/10.1016/j.talanta.2020.121743.
11. Campanale C, Massarelli C, Savino I, Locaputo V, Uricchio VF. A Detailed Review Study on Potential Effects of Microplastics and Additives of Concern on Human Health. Int J Environ Res Public Health. 2020. https://doi.org/10.3390/ijerph17041212.
12. Cohen DJ, Reynolds MR. Interpreting the results of cost-effectiveness studies. J Am Coll Cardiol. 2008;52(25):2119–26.
13. Cowger W, Gray A, Christiansen SH, DeFrond H, Deshpande AD, Hemabessiere L, Lee E, Mill L, Munno K, Ossmann BE, Pittroff M. Critical review of processing and classification techniques for images and spectra in microplastic research. Appl Spectrosc. 2020;74(9):989–1010.
14. Cutroneo L, Reboa A, Besio G, Borgogno F, Canesi L, Canuto S, Dara M, Enrile F, Foriosol, Greco G, Lenoble V. Microplastics in seawater: sampling strategies, laboratory methodologies, and identification techniques applied to port environment. Environ Sci Pollut Res. 2020;27:8938–52.
15. Cylus J, Papanicolas I, Smith PC, eds. Health System Efficiency: How to Make Measurement Matter for Policy and Management. Copenhagen, Denmark: European Observatory on Health Systems and Policies; 2016. Health Policy Series No. 46.
16. Erni-Cassola G, Gibson MI, Thompson RC, Christie-Oleza JA. Lost, but found with Nile red: a novel method for detecting and quantifying small microplastics (1 mm to 20 µm) in environmental samples. Environ Sci Technol. 2017;51(23):13641–8.
17. European Commission. Horizon Europe (HORIZON) Euratom Research and Training Programme (EURATOM) General Model Grant Agreement EIC Accelerator Contract, Version 1.1. (2022). Available at https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/common/agr-contr/general-mga_horizon-euratom_en.pdf#page=25
18. Eurostat. Average full time adjusted salary per employee. 2022. https://ec.europa.eu/eurostat/cache/metadata/en/nama_10_fte_esms.htm. Accessed Jan 2022.
19. Fauser, P., Vorkamp, K., Strand, J. Residual additives in marine microplastics and their risk assessment – A critical review, Marine Pollution Bulletin, Volume 177, 2022, https://doi.org/10.1016/j.marpolbul.2022.113467.
20. Gao Z, Cizdziel JV, Wontor K, Clisham C, Focia K, Rausch J, Jaramillo-Vogel D. On airborne tire wear particles along roads with different traffic characteristics using passive sampling and optical microscopy, single particle SEM/EDX, and µ-ATR-FTIR analyses. Front Environ Sci. 2022;10:2136.
21. Garber AM, Sculpher MJ. Cost effectiveness and payment policy. In Handbook of health economics Elsevier. 2011;2:471–97.
22. Gillibert R, Magazzù A, Callegari A, Bronte-Ciriza D, Foti A, Donato MG, Maragò OM, Volpe G, de La Chapelle ML, Lagarde F, Gucciardi P.G. Raman tweezers for tire and road wear micro-and nanoparticles analysis. Environmental Science: Nano. 2022;9(1):145–61.
23. Güven O, Gökdağ K, Jovanović B, Kıdeyş AE. Microplastic Litter Composition of the Turkish Territorial Waters of the Mediterranean Sea, and its Occurrence in the Gastrointestinal Tract of Fish. Environ Pollut. 2017;223:286–94.
24. Hanvey JS, Lewis PJ, Lavers JL, Crosbie ND, Pozo K, Clarke BO. A review of analytical techniques for quantifying microplastics in sediments. Anal Methods. 2017;9(9):1369–83.
25. Hartmann NB, Hüffer T, Thompson RC, Hassellöv M, Verschoor A, Daugaard AE, Rist S, Karlsson T, Brennholt N, Cole M, Herrling MP, Hess MC, Ivleva NP, Lusher AL, Wagner M. Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. Environ Sci Technol. 2019;53:1039–47. https://doi.org/10.1021/acs.est.8b05297.
26. Hermsen E, Mintenig SM, Besseling E, Koelmans AA. Quality criteria for the analysis of microplastic in biota samples: a critical review. Environ Sci Technol. 2018;52(18):10230–40.
27. Hidalgo-Ruz V, Gutow L, Thompson RC, Thiel M. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ Sci Technol. 2012;46(6):3060–75.
28. Hurley RR, Lusher AL, Olsen M, Nizzetto L. Validation of a Method for Extracting Microplastics from Complex, Organic-Rich, Environmental Matrices. Environ Sci Technol. 2018;52(13):7409–17. https://doi.org/10.1021/acs.est.8b01517.
29. Ivleva NP. Chemical analysis of microplastics and nanoplastics: Challenges, advanced methods, and perspectives. Chem Rev. 2021;121(19):11886–936.
30. Jiang J, Wang X, Ren H, Cao G, Xie G, Xing D, Liu B. Investigation and fate of microplastics in wastewater and sludge filter cake from a wastewater

treatment plant in China. Sci Total Environ. 2020;746:141378. https://doi.org/10.1016/j.scitotenv.2020.141378.
31. Kopke K, Meyers N, Dozier A, Fitzgerald E, Power O-P, Agnew S, Everaert G, De Witte B. Scientist Perspectives on the Cost-Effectiveness of Microplastic Analysis Methods for Seawater Samples: ANDROMEDA Workshop 1 Event Summary & Participant Recommendations on Cost-effectiveness. 1-10. JPI Oceans project. 2023a. http://dx.doi.org/10.13140/RG.2.2.17205.86241.
32. Kopke K, Meyers N, Dozier A, Fitzgerald E, Power O-P, Agnew S, Sempéré R. Policy & Decision Makers Perspectives on the Cost-Effectiveness of Microplastic Analysis Methods for Seawater Samples: ANDROMEDA Workshop 2 Event Summary & Participant Recommendations on Cost-effectiveness. 1-11. JPI Oceans project. 2023b. http://dx.doi.org/10.13140/RG.2.2.27272.19204.
33. Lenz R, Enders K, Stedmon CA, Mackenzie DM, Nielsen TG. A critical assessment of visual identification of marine microplastic using Raman spectroscopy for analysis improvement. Mar Pollut Bull. 2015;100(1):82–91.
34. Li Q, Wu J, Zhao X, Gu X, Ji R. Separation and identification of microplastics from soil and sewage sludge. Environ Pollut. 2019;254:113076.
35. Liu F, Olesen KB, Borregaard AR, Vollertsen J. Microplastics in urban and highway stormwater retention ponds. Sci Total Environ. 2019;671:992–1000. https://doi.org/10.1016/j.scitotenv.2019.03.416.
36. Löder, M. G. J.; Gerdts, G. In Marine Anthropogenic Litter; Bergmann, M., Gutow, L., Klages, M., Eds.; Springer International Publishing, 2015
37. Löder MGJ, Imhof HK, Ladehoff M, Löschel LA, Lorenz C, Mintenig S, Piehl S, Primpke S, Schrank I, Laforsch C, Gerdts G. Enzymatic Purification of Microplastics in Environmental Samples. Environ Sci Technol. 2017;51(24):14283–92. https://doi.org/10.1021/acs.est.7b03055.
38. Maes T, Jessop R, Wellner N, Haupt K, Mayes AG. A rapid-screening approach to detect and quantify microplastics based on fluorescent tagging with Nile Red. Scientific reports. 2017;7(1):44501. https://doi.org/10.1038/srep44501
39. Mariano S, Tacconi S, Fidaleo M, Rossi M, Dini L. Micro and nanoplastics identification: classic methods and innovative detection techniques. Frontiers in toxicology. 2021;3:636640.
40. Masura, J., Baker, J., Foster, G., & Arthur, C. (2015). Laboratory Methods for the Analysis of Microplastics in the Marine Environment: Recommendations for quantifying synthetic particles in waters and sediments.
41. Meyers N, Catarino AI, Declercq AM, Brenan A, Devriese L, Vandegehuchte M, De Witte B, Janssen C, Everaert G. Microplastic detection and identification by Nile red staining: Towards a semi-automated, cost-and time-effective technique. Sci Total Environment. 2022;823:153441.
42. Meyers, N.; Kopke, K.; Buhhalko, N.; Mattsson, K.; Janssen, C.R.; Everaert, G.; De Witte, B.; Flanders Research Institute for Agriculture, Fisheries and Food; Flanders Marine Institute; Laboratory of Environmental Toxicology and Aquatic Ecology (Ghent University); SFI Research Centre for Energy, Climate and Marine research and innovation (University College Cork); Department of Marine Systems (Tallinn University of Technology); Department of Marine Sciences (University of Gothenburg); (2023): ANDROMEDA predictive tools for estimating microplastic analysis costs. Marine Data Archive. https://doi.org/10.14284/636
43. Miller, J.V., Maskrey, J.R., Chan, K., Unice, K.M. Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC-MS) Quantification of Tire and Road Wear Particles (TRWP) in Environmental Matrices: Assessing the Importance of Microstructure in Instrument Calibration Protocols. 2021. Analytical Letters, 2022, 55:6, 1004–1016, https://doi.org/10.1080/00032719.2021.1979994
44. Mishra A, Buhhalko N, Lind K, Lips I, Liblik T, Väli G, Lips U. Spatiotemporal Variability of Microplastics in the Eastern Baltic Sea. Front Mar Sci. 2022;9:875984. https://doi.org/10.3389/fmars.2022.875984.
45. Montoto-Martínez T, Meléndez-Díez C, Melián-Ramírez A, Hernández-Brito JJ, Gelado-Caballero MD. Comparison between the traditional Manta net and an innovative device for microplastic sampling in surface marine waters. Mar Pollut Bull. 2022;185:114237.
46. Neukermans G, Ruddick K, Loisel H, Roose P. Optimization and quality control of suspended particulate matter concentration measurement using turbidity measurements. Limnol Oceanogr Methods. 2012;10(12):1011–23.
47. Office of Tax Analysis (1990), "Depreciation of Scientific Instruments," Washington, Office of Tax Analysis, U.S. Department of the Treasury, March.
48. Okoffo ED, O'Brien S, O'Brien JW, Tscharke BJ, Rauert C, Rødland ES, Ribeiro F, Burrows SD, Toapanta T, Mueller JF, Thomas KV. Does size matter? Quantification of plastics associated with size fractionated biosolids. Sci Total Environ. 2022;811:152382.
49. Parker-Jurd FN, Napper IE, Abbott GD, Hann S, Thompson RC. Quantifying the release of tyre wear particles to the marine environment via multiple pathways. Mar Pollut Bull. 2021;172:112897.
50. Pasquier G, Doyen P, Kazour M, Dehaut A, Diop M, Duflos G, Amara R. Manta net: The golden method for sampling surface water microplastics in aquatic environments. Front Environ Sci. 2022;10:811112.
51. Pfeiffer F, Fischer EK. Various Digestion Protocols Within Microplastic Sample Processing Evaluating the Resistance of Different Synthetic Polymers and the Efficiency of Biogenic Organic Matter Destruction. Front Environ Sci. 2020;8:572424. https://doi.org/10.3389/fenvs.2020.572424.
52. Prata, J.C., da Costa, J.P., Duarte, A.C., Rocha-Santos, T. Methods for sampling and detection of microplastics in water and sediment: a critical review. (2018). TrAC Trends Anal Chem. 2019;110:150–159. https://doi.org/10.1016/j.trac.2018.10.029.
53. Prata JC, Reis V, Matos JT, da Costa JP, Duarte AC, Rocha-Santos T. A new approach for routine quantification of microplastics using Nile Red and automated software (MP-VAT). Sci Total Environ. 2019;690:1277–83.
54. Primpke S, Christiansen SH, Cowger W, De Frond H, Deshpande A, Fischer M, Holland EB, Meyns M, O'Donnell BA, Ossmann BE, Pittroff M. Critical assessment of analytical methods for the harmonized and cost-efficient analysis of microplastics. Appl Spectrosc. 2020;74(9):1012–47.
55. Primpke S, Lorenz C, Rascher-Friesenhausen R, Gerdts G. An automated approach for microplastics analysis using focal plane array (FPA) FTIR microscopy and image analysis. Anal Methods. 2017;9(9):1499–511.
56. Qiao R, Deng Y, Zhang S, Wolosker MB, Zhu Q, Ren H, Zhang Y. Accumulation of different shapes of microplastics initiates intestinal injury and gut microbiota dysbiosis in the gut of zebrafish. Chemosphere. 2019;236:124334.
57. Rødland, E.S., Samanipour, S.,Rauert, C., Okoffo, E.D., Reid, M.J., Heier, L.S., Lind, O.C., Thomas, K.V., Meland, S. A novel method for the quantification of tire and polymer-modified bitumen particles in environmental samples by pyrolysis gas chromatography mass spectroscopy, Journal of Hazardous Materials, Volume 423, Part A, 2022, 127092, https://doi.org/10.1016/j.jhazmat.2021.127092.
58. Sana SS, Dogiparthi LK, Gangadhar L, Chakravorty A, Abhishek N. Effects of microplastics and nanoplastics on marine environment and human health. Environ Sci Pollut Res. 2020;27:44743–56. https://doi.org/10.1007/s11356-020-10573-x.
59. Santos LH, Insa S, Arxé M, Buttiglieri G, Rodríguez-Mozaz S, Barceló D. Analysis of microplastics in the environment: Identification and quantification of trace levels of common types of plastic polymers using pyrolysis-GC/MS. MethodsX. 2023;10:102143.
60. Schwarzer M, Brehm J, Vollmer M, Jasinski J, Xu C, Zainuddin S, Fröhlich T, Schott M, Greiner A, Scheibel T, Laforsch C. Shape, size, and polymer dependent effects of microplastics on Daphnia magna. J Hazard Mater. 2022;426:128136.
61. Sendra, M., Pereiro, P., Figueras, A., Novoa, B. An integrative toxicogenomic analysis of plastic additives, Journal of Hazardous Materials, Volume 409, 2021. https://doi.org/10.1016/j.jhazmat.2020.124975.
62. Shim, W.J., Song, Y.K., Hong, S.H., Jang, M., Identification and quantification of microplastics using Nile red staining. Mar. Pollut. Bull. 2016, 113, 469–476. https://doi.org/10.1016/j.marpolbul.2016.10.049.
63. Stanton T, Johnson M, Nathanail P, Gomes RL, Needham T, Burson A. Exploring the efficacy of Nile red in microplastic quantification: a costaining approach. Environ Sci Technol Lett. 2019;6(10):606–11.
64. Tan S, Taylor JA, Passeport E. Efficient Prediction of Microplastic Counts from Mass Measurements. ACS ES&T Water. 2022;2(2):299–308.
65. Thornton Hampton, L.M., Brander, S.M., Coffin, S., Cole, M., Hermabessiere, L., Koelmans, A.A., Rochman, C.M. Characterizing microplastic hazards: which concentration metrics and particle characteristics are most informative for understanding toxicity in aquatic organisms?. Micropl.&Nanopl. 2, 20 (2022). https://doi.org/10.1186/s43591-022-00040-4
66. Thiele CJ, Hudson MD, Russell AE, Saluveer M, Sidaoui-Haddad G. Microplastics in fish and fishmeal: an emerging environmental challenge? Sci Rep. 2021;11(1):2045.
67. Thomas D, Schütze B, Heinze WM, Steinmetz Z. Sample Preparation Techniques for the Analysis of Microplastics in Soil—A Review. Sustainability. 2020;12:9074. https://doi.org/10.3390/su12219074.

68. Torres FG, Dioses-Salinas DC, Pizarro-Ortega CI, De-la-Torre GE. Sorption of chemical contaminants on degradable and non-degradable microplastics: Recent progress and research trends. Sci Total Environ. 2021;757:143875.
69. Valente T, Ventura D, Matiddi M, Sbrana A, Silvestri C, Piermarini R, Jacomini C, Costantini ML. Image processing tools in the study of environmental contamination by microplastics: reliability and perspectives. Environ Sci Pollut Res. 2023;30:298–309. https://doi.org/10.1007/s11356-022-22128-3.
70. Veerasingam, S., Ranjani, M., Venkatachalapathy, R., Bagaev, A., Mukhanov, Daria Litvinyuk, D., Mugilarasan, M., Gurumoorthi, K., Guganathan, L., Aboobacker, V.M., Vethamony, P. Contributions of Fourier transform infrared spectroscopy in microplastic pollution research: A review, Critical Reviews in Environmental Science and Technology. 2021;51(22):2681–743. https://doi.org/10.1080/10643389.2020.1807450.
71. Wagner S, Hüffer T, Klöckner P, Wehrhahn M, Hofmann T, Reemtsma T. Tire wear particles in the aquatic environment-a review on generation, analysis, occurrence, fate and effects. Water Res. 2018;139:83–100.
72. Wang W, Ge J, Yu X. Bioavailability and toxicity of microplastics to fish species: A review. Ecotoxicol Environ Saf. 2020;189:109913.
73. World Bank. GNI per capita, Atlas method (current US$). 2021. Retrieved from https://data.worldbank.org/indicator/NY.GNP.PCAP.CD?view=map&year=2021. Accessed Nov 2022.
74. Zarfl C. Promising techniques and open challenges for microplastic identification and quantification in environmental matrices. Anal Bioanal Chem. 2019;411:3743–56. https://doi.org/10.1007/s00216-019-01763-9.

Publisher's Note