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Monitoring macroplastics in aquatic and terrestrial ecosystems: Expert survey reveals visual and drone-based census as most effective techniques

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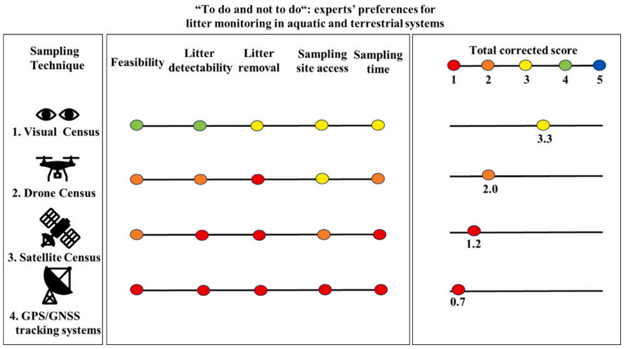
HIGHLIGHTS

- Nearly 50 experts were consulted regarding monitoring macroplastic litter in aquatic and terrestrial ecosystems.
- Pros and cons of four sampling techniques to collect data on plastic litter were addressed and evaluated.
- Visual and drone-based censuses as best approaches for plastic litter monitoring.
- Satellite imagery and GPS tracking hold potential and future options, but their use remains limited.
- Machine or deep learning can assist in the analysis of plastic litter monitoring.

GRAPHICAL ABSTRACT



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ABSTRACT

Anthropogenic litter, such as plastic, is investigated by the global scientific community from various fields employing diverse techniques. The goal is to assess and finally mitigate the pollutants' impacts on the natural environment. Plastic litter can accumulate in different matrices of aquatic and terrestrial ecosystems, impacting both biota and ecosystem functioning. Detection and quantification of macroplastics, and other litter, can be realized by jointly using visual census and remote sensing techniques. The primary objective of this research was to identify the most effective approach for monitoring macroplastic litter in riverine and marine environments through a comprehensive survey based on the experiences of the scientific community. Researchers involved in plastic pollution evaluated four litter occurrence and flux investigation methods (visual census, drone-based surveys, satellite imagery, and GPS/GNSS trackers) through a questionnaire. Traditional visual census and drone deployment were deemed as the most popular approaches among the 46 surveyed researchers, while satellite imagery and GPS/GNSS trackers received lower scores due to limited field validation and short performance ranges, respectively. On a scale from 0 to 5, visual census and drone-based surveys obtained 3.5 and 2.0, respectively, whereas satellite imagery and alternative solutions received scores lower than 1.2. Visual and drone censuses were used in high, medium and low-income countries, while satellite census and GPS/GNSS trackers were mostly used in high-income countries. This work provides an overview of the advantages and drawbacks of litter investigation techniques, contributing *i)* to the global harmonization of macroplastic litter monitoring and *ii)* providing a starting point for researchers and water managers approaching this topic. This work supports the selection and design of reliable and cost-effective monitoring approaches to mitigate the ambiguity in macroplastic data collection, contributing to the global harmonization of macroplastic litter monitoring protocols.

1. Introduction

The large amount of plastic litter in aquatic and terrestrial environments is a cause for concern, as it can harm biota, ecosystems, and human health (Blettler and Wantzen, 2019; Cássio et al., 2022; Allen et al., 2022). Both land-based and marine-based sources have been identified; the former includes the mismanagement of solid waste that reaches the sea mainly via rivers (Mai et al., 2020; González-Fernández et al., 2021); the second includes mismanagement from fishing and, generally, boat-based activities, and aquaculture (GESAMP, 2019; Morales-Caselles et al., 2021; Andriolo and Gonçalves, 2022; Andriolo and Gonçalves, 2023; Galgani et al., 2023). However, it has been hypothesized that over 90 % of plastic waste generated on land is not accounted for in marine plastic litter (Van Emmerik et al., 2022; Gallitelli and Scalici, 2024). Evidence suggests that plastic litter can accumulate in fluvial habitats without reaching the sea (Tramoy et al., 2020; Liro et al., 2020; Weiss et al., 2021; Van Emmerik et al., 2022; Gallitelli et al., 2024). The plastic retained in riverine habitats will henceforth be referred to as “land-retained plastic”. Although the scientific community has mainly focused on marine habitats since the 1970s (Carpenter and Smith Jr., 1972), the interest in freshwater has been exponentially growing over the last decades (Blettler and Mitchell, 2021; Garello et al., 2021; Kumar et al., 2021; Gallitelli and Scalici, 2023). The studies highlighted that macroplastics may get entangled to, be used for building nests or cases, or be ingested by freshwater biota in the same manner as marine biota do (Blettler and Mitchell, 2021; Azevedo-Santos et al., 2021; Battisti et al., 2023), presenting a risk to the freshwater ecosystems too.

Several efforts have been made to mitigate plastic pollution in aquatic (i.e., rivers and seas) and terrestrial (i.e., coastal and riparian zones) systems. Over the last decades, various litter monitoring strategies have been recommended, and implemented in many places, formalizing several recommended protocols for in-situ surveys (GESAMP, 2019; OSPAR Commission, 2010; UNEP, United Nations Environment Programme, 2020; Galgani et al., 2024). Several monitoring campaigns have been conducted, in various regions and for different reasons such as to (1) estimate emissions into the ocean, (2) monitor the transport and fluxes of plastic through ecosystems, (3) measure the abundance of specific items, and (4) conduct long-term monitoring of trends or effects studies. Monitoring litter floating or stranded on beaches and riverbanks is generally performed by visual census or through the application of remote sensing techniques. Riverine floating, riverbank, and vegetation litter have been mainly monitored by using visual census techniques (Tramoy et al., 2020; van Emmerik and Schwarz, 2020; González-Fernández et al., 2021; Hurley et al., 2023; Gallitelli et al., 2024).

Remote sensing technologies have arisen to overcome visual census limitations (Maximenko et al., 2019). Drone-based litter surveys have been applied on riverine, marine and coastal environments since drones can fly over large and remote areas. Drones operate autonomously and provide high-resolution images allowing detection and mapping of litter stranded on beaches (Martin et al., 2018; Andriolo et al., 2021a) and dunes (Corbau et al., 2023), as well as litter floating in marine (Garcia-Garin et al., 2020b) and river waters (Geraeds et al., 2019). The drone camera is usually set to capture photos perpendicular to the flight direction, while the flight altitude is chosen based on camera properties to obtain an image pixel spatial resolution, expressed as Ground Sampling Distance (GSD), suitable to detect macrolitter items (>2.5 cm; hereafter “plastic litter” or simply “litter”). A suitable GSD has been set between 0.5 cm/px and 1.25 cm/p (Andriolo et al., 2023). As a rule of thumb, the detection limit of litter objects in drone images is approximately four times the GSD (Torsvik et al., 2020; Li et al., 2023). Litter items can be marked on images both manually (Andriolo et al., 2021b) and/or by automated detection algorithms (Duarte et al., 2020; Pinto et al., 2021). Besides litter classification, images can be exploited to retrieve the size of litter (Merlino et al., 2020), estimate the weight and volume of litter bulk (Kako et al., 2020; Andriolo et al., 2024), and generate categorical litter maps to identify likely pollution hotspots (Andriolo et al., 2020). Despite the relatively limited flight time and some challenges associated to the identification of litter items in the collected images, drone-based litter surveys have been shown as a valuable approach to advance knowledge on litter dynamics in natural environments. The development of a standardized protocol for drone plastic litter data collection, analysis and assessments would further enhance the intercomparison among surveys (Gonçalves et al., 2022).

During the last decade, significant research efforts have also been spent for employing satellite imagery for spotting plastic litter from space, for the identification of litter patches in oceans (Topouzelis et al., 2019), rivers (Tran-Thanh et al., 2022; Sakti et al., 2023), and recently for the large-scale monitoring of floating marine plastic litter (Cózar et al., 2024). Research utilizing satellite systems, such as the Copernicus Sentinel-2 missions and WorldView-3, hold great potential for enabling comprehensive global monitoring of plastic pollution across vast areas, especially in remote or inaccessible regions, although the higher spatial resolution missions tend not to systematically acquire data over the open ocean (Biermann et al., 2020; Lavender, 2022). Some limitations have been identified for the use of satellite data for marine litter detection such as the low spectral and/or spatial resolution, the unknown of marine spectral signatures (Corbari et al., 2023) and the influence of cloud cover on data acquisition (Garaba and Dierssen, 2020).

Alternative solutions to monitor plastic litter in complex and/or inaccessible environments, employing varying types of sensors, have also been investigated and proposed by the research community. With regards to plastic litter in the water column, underwater drones, GPS, Radar and Eco Doppler tools were employed in oceans and rivers (Tramoy et al., 2021; Broere et al., 2021; Boon et al., 2023). Escobar-Sánchez et al. (2022) demonstrated the potential of aerial (UAV) and underwater (ROV) drones as monitoring tools for floating and submerged litter in coastal sites. However, the influence of water conditions (water transparency, colour, depth, bottom substrate), plastic litter characteristics (colour and size), and method settings (flight/dive height) affect the detection accuracy of litter (Escobar-Sánchez et al., 2022). Remote sensing tools could have the same cost and efficiency as current on-boat observation or scuba diving methods (e.g., visual census, Escobar-Sánchez et al., 2022). To date, therefore, different complementary approaches, combined with visual census, could provide a more complete and comprehensive monitoring of plastic litter in aquatic and terrestrial habitats.

Plastic litter tracking systems working with Global Positioning Systems and Global Navigation Satellite Systems (hereafter, GPS/GNSS litter tracking systems, Madry, 2015) offer valuable assistance in unveiling sites of plastic litter accumulation and highlight the transport dynamics of plastic along a river (Tramoy et al., 2021; Boon et al., 2023), thereby facilitating cleanup efforts and informing policy decisions (Mani et al., 2023). GPS/GNSS litter tracking systems have been used to approximate floating litter trajectories and fate. However, these technologies have very specific and narrow applications, targeting alternative research questions and may require calibration and validation, and their effectiveness could be constrained in highly dynamic environments or areas with dense vegetation (Table 1, Tramoy et al., 2021); recently, this technology has been used to track the movement of plastic litter pollution (Duncan et al., 2020).

Given the array and diversity of techniques available for monitoring plastic litter, this paper investigates if there is a predominant technique that allows the best feasible sampling approach. The aim was to foster harmonization of plastic litter monitoring methods by identifying the main advantages/disadvantages of each technique. Considering that litter census and monitoring are pivotal to understanding litter accumulation and fate in aquatic and terrestrial systems, this study aimed to investigate the most common macroplastic litter monitoring techniques used by the researchers working on this topic. This paper synthesizes the current knowledge on litter sampling techniques, offering insights into the strengths and limitations of each litter monitoring method to be relevant to ongoing environmental research. Moreover, due to the lack of methodological harmonization, this paper consolidates diverse opinions from nearly 50 researchers globally, comparing multiple monitoring methods in different environments and further contributing to the ongoing methodological standardization efforts.

The results of our survey, highlights a considerable delay in the harmonization of macroplastic monitoring techniques across different ecosystems, a crucial step towards standardized global practices. By using a questionnaire, we asked 100 researchers in the field of macroplastic pollution to evaluate different techniques used in aquatic and terrestrial ecosystems (i.e., riverine riparian areas, marine/coastal systems, lakes, wetlands, etc). We tested two key questions about plastic litter monitoring in both aquatic and terrestrial habitats.

The first one regards the assessment of the techniques by river vs ocean scientists. As marine investigations started decades ago when drone and GPS/GNSS tracking systems were not readily available, would marine scientists be more inclined to use traditional visual census techniques over more modern methods? Second, is the choice of census techniques dependent on the researcher’s background disciplines (e.g., river, ocean, and coast scientists)?

All the questions asked to the experts are aimed at understanding what is the best option for plastic litter monitoring, to provide (i) a starting point for early career scientists approaching these topics and (ii) drive our monitoring activities towards global harmonization. These actions are pivotal to allow findings comparison and, therefore, to understand and spot plastic accumulation areas, as first steps to mitigate plastic pollution.

To the Author's knowledge, this is the first work investigating the opinion of the scientific community about the feasibility, advantages and limitations of the most common techniques employed for plastic litter monitoring.

2. Methods

To gather the plastic pollution research community's perspectives/opinions on available techniques for surveying macroplastic litter in aquatic and terrestrial environments, we developed a questionnaire using Google Forms. The questionnaire was specifically developed for this study. Data gathering and collection were performed following Cooper et al. (2006). Overall, 100 researchers in the field of riverine, marine, and coastal plastic litter monitoring, working with visual census and remote sensing techniques were selected and contacted. The researchers were selected based on a search on Web of Science, considering experts who authored at least one publication and have done at least three years of research on this topic (i.e., obtained master's degree plus being a doctoral student). Out of 100 experts invited, 46 researchers specializing in plastic litter replied to the questionnaire, providing their expert judgment and perceptions.

A total of 11 questions were included in the questionnaire which was sent to the participants by allowing a two-week response window (see Supplementary Materials). The questionnaire was composed of five sections of questions related to the main sampling techniques used to identify and count macroplastic litter in aquatic and terrestrial habitats (i.e., visual census, drone, satellite, and GPS/GNSS litter tracking systems census). The first section gathered personal information of researchers, such as age (identified through 5 classes), academic position (i.e., PhD Student, Postdoc Researchers, Researchers, Professors, Non-academic, others), and the study area of the experts (i.e., River, marine, dune/coastal, wetland, urban water system, estuary, and lake). In general, the researchers answered based on the ecosystems they usually sample to provide the most appropriate expert judgment.

The second section of questions dealt with specific plastic litter sampling techniques (i.e., Visual Census, Drone Census, Satellite Census, and GPS/GNSS litter tracking systems Census, hereafter named with acronyms VC, DC, SC, and GC, respectively). In particular, the suitability of a sampling technique was evaluated through a combination of 5 features:

1) the "feasibility", which indicates the capability of performing the survey and detecting plastic litter;
2) the "litter detectability", which evaluates the suitability of spotting plastic litter in the environment;
3) the "litter removal", which indicates the possibility of removing plastic litter from the environment after detection;
4) the "sampling site access", which regards difficulties/possibility of accessing the study site to be sampled;
5) the "sampling time", which evaluates the total time needed to perform the survey.

The third section of questions focused on identifying the best features of the four sampling techniques. The experts were asked to evaluate, for each technique, which feature was the most feasible and useful to monitor plastic pollution.

Lastly, the fourth section of questions addressed the increasing use of automated algorithms (i.e., Machine Learning and Artificial Intelligence, hereafter ML and AI), which can automate and accelerate the processing of images collected by drones, cameras, and satellites.

2.1. Data analysis

The experts were asked to evaluate the suitability of the four techniques for plastic litter monitoring with a score ranging from 1 to 5 (i.e., 1 is the lowest score and 5 the highest score). The option "I do not know" was included as a possible answer too. The responses provided by the researchers were used to extract data values and calculate average scores. However, it is important to consider that since many researchers work only on one or two sampling techniques, their perceptions and answers could be biased towards their preferred sampling method. Thus, known or used techniques may receive higher scores from the researchers who regularly use them. To adjust this bias, the score was corrected taking into consideration the number of "I don't know" answers. Specifically, the correction factor applied reduces the score the more unknown answers are received. Considering the "I do not know" answers, given that the uncertainty gets higher when the score increases, we used the reciprocal value of the "I do not know" and the score was multiplied by the uncertainty factor as in Eq. (1):

$$\textit{Corrected score} = \textit{mean of the score x} \left(1 - \left(\textit{number of} \text{ ``}\textit{I do not know}\text{''} / \textit{number of total answers}\right)\right) \tag{1}$$

The result section will only show the corrected scores resulting from Eq. (1). The total score is shown as an average of all the feature scores with its standard error.

Before performing statistical tests, homoscedasticity and normality of the data were checked. When data assume a normal distribution, parametric tests were used like ANOVA. All these analyses were performed by using GraphPad software. To test if there are any differences in the score between techniques and the sampling features, we performed a one-way ANOVA. Then, to test the same differences in the score among river, marine, and coastal scientists, we carried out a two-way ANOVA. If the results were significant, we performed a Dunn post hoc test to reveal significant differences between pairs.

Given that certain techniques might be more expensive than others, we expect differences in the implementation of the techniques considered based on the income of the interviewee's country. Countries were divided into three groups considering their GDP (i.e., low, medium, and high-income countries). After dividing the countries by GDP groups (World Bank, 2024), we compared the number of studies performed with a certain sampling technique from a given country. To test if there were any significant differences between sampling techniques and GDP, we performed an ANOVA test.

3. Results

Among the 100 questionnaires sent, 46 responses were received, with 6.5 % being non-academic and 93.5 % being academic researchers. Young researchers (i.e., PhD and PostDoc Researchers) were 37.2 % while Senior Researchers (i.e., Researchers and Professors) were 62.8 %. Researchers answering this questionnaire mostly focused on riverine (41.3 %) and marine (26.1 %) ecosystems (Fig. 1).

Regarding the most suitable sampling techniques to detect plastic litter (Fig. 2), the experts scored Visual Census (VC) and Drone Census (DC) the highest (3.3 ± 1.1 and 2.0 ± 1.1, out of 5.0 respectively). Conversely, satellite census (SC) and GPS/GNSS litter tracking systems census (GC) received the lowest scores (1.2 ± 1.1 and 0.7 ± 1.2, out of 5.0 respectively). There was a significant difference among sampling

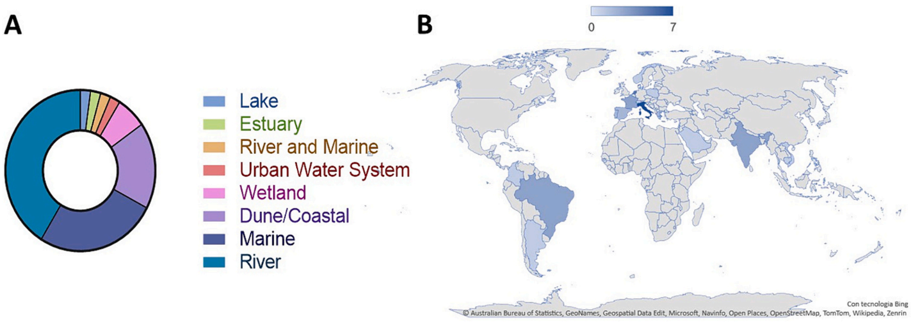

Fig. 1. (A) Study areas where the experts focus their research. (B) Number of studies (i.e., colour scale from 0 to 7) performed in the countries.

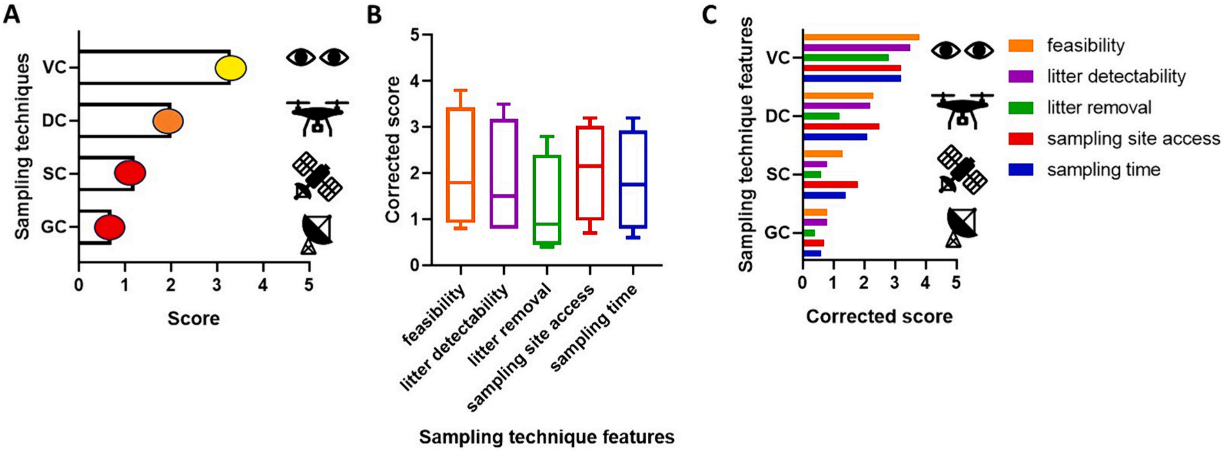

Fig. 2. (A) The corrected score for the most suitable sampling techniques for monitoring plastic litter. The colors from blue to red indicate the average score ranging between low and high values (red to blue, respectively). (B) Boxplots for the average corrected score for sampling technique features and (C) bar charts of the average corrected score for each feature and each sampling technique. VC = visual census, DC = drone census, SC = satellite census, GC = GPS/GNSS litter tracking systems census.

features and sampling techniques (F = 8.878, $p < 0.05$; F = 89.22, $p < 0.0001$, respectively). Dunn *post-hoc* tests revealed significant differences between all pairwise comparisons except GC and SC ($p > 0.05$). Concerning the sampling features, the feasibility and plastic litter removal pairwise comparison resulted to be significantly different (F = 1.150, $p < 0.05$, Fig. 2C). Regarding the use of sampling techniques, both VC and DC were mainly used in high-income countries, although they were also utilized in some medium and low-income countries. In contrast, SC and GC were mostly used in high-income countries ($H' = 7.903$, $p = 0.005$).

The most useful feature of the four sampling techniques (Fig. 2B, C) was "sampling site access", which received the highest score (4.1 out of 5.0), while "litter removal" had the lowest score (1.3 out of 5.0, see Fig. 2B, C). Feasibility, litter detectability and litter removal were highest for VC (4.3, 3.9, and 3.5 out of 5.0 respectively, Fig. 2C). Sampling site access and sampling time received the highest scores for DC (4.1 and 3.7 out of 5.0, Fig. 2C). Regarding each feature, the difference between corrected score values resulted to be significant (F = 7.182, $p < 0.001$). In detail, Dunn's post-hoc test revealed significant differences between VC and GC, and VC and SC ($p < 0.05$).

When comparing the scores given by researchers with different backgrounds (i.e., river, ocean, and coastal scientists, Fig. 3), riverine scientists gave the highest scores to VC and DC (mostly for feasibility and sampling site access, respectively) and lower scores to SC and GC

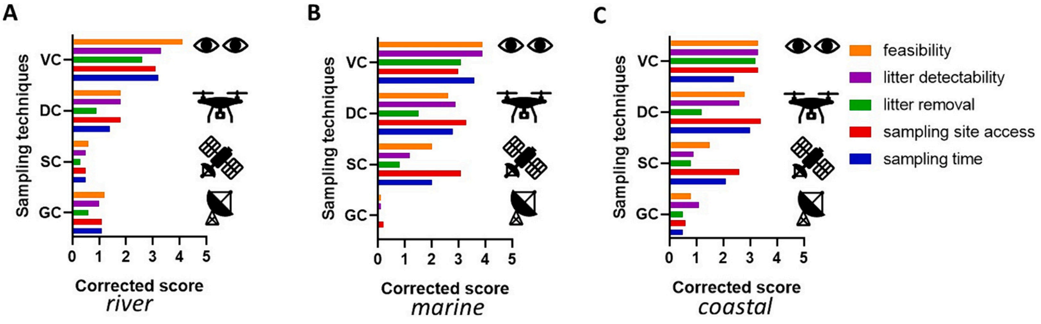

Fig. 3. Score for sampling technique features by (A) river, (B) marine, and (C) coastal scientists. Plastic litter in "rivers" indicates studies conducted in water (floating), on riverbanks, and in vegetation (aquatic and riparian). "Marine" refers to studies conducted in seawater, and "coastal" refers to plastic litter on beaches, and vegetation on dunes, mangroves, and estuaries. VC = visual census, DC = drone census, SC = satellite census, GC = GPS/GNSS litter tracking systems census.

(mostly for litter removal and litter detectability). Specifically, for river and coastal scientists, VC was the most suitable technique with SC being the least usable, while for marine scientists VC was the most suitable technique with GC being the least used (Fig. 3). We obtained a non-significant difference among sampling features by river, marine, and coastal scientists (F = 0.3107, *p* = 0.87).

When asked about the use of machine learning (ML) or artificial intelligence (AI) tools, 47.8 % of experts declared to have used AI and ML to assist in plastic litter census and to fasten and improve image processing tasks, while 52.2 % have still not used these techniques. However, 91.3 % of experts suggested using AI for future research. Moreover, the experts reported that they already use ML techniques or are considering adding deep learning methodologies.

4. Discussion

We asked 100 experts to compare plastic litter sampling techniques based on their own experience, and we computed a corrected score based on the 46 answers obtained from the questionnaire. All replying experts have been involved in litter monitoring working on macrolitter and were qualified as experts to evaluate the advantages and disadvantages of each sampling technique in different habitats. This framework could be useful for early career scientists who have started to study these topics or scientists who are interested in selecting and applying one of those techniques based on the consensus shared by experts on this topic. Moreover, the findings of this work might lead to more reliable, cost-effective monitoring, which is crucial for policymakers and mitigation efforts. This could be particularly important in developing a foundational reference for future studies aimed at refining or implementing large-scale monitoring protocols worldwide. Furthermore, this study may help managers in developing appropriate plastic monitoring guidelines. For example, different technical approaches (VC, DC, SC, GC and so on) could show a different level of 'technological readiness' along an evaluation scale (see the TRL – Technological Readiness Level – approach in Aliani et al., 2023). TRL scale classifies techniques and methods in different phases (basic research, applied research, in-development, and implementation). Only if techniques (and analytical) approaches fail, scientists and managers could adopt an expert-based approach (Aliani et al., 2023).

In our case, we used expert judgment, highlighting how these sampling techniques could be used to answer the research questions, until now.

4.1. Visual and drone census as preferred sampling techniques

After applying the correction factor (see Method section), significant differences were revealed among the sampling techniques, VC and DC obtained the highest scores, while the lowest scores for were assigned to GC and SC. Regarding the variability in the responses, the boxplot in Fig. 2B shows a fairly high range of scores with the standard deviations being relatively low. This means that there is a general *consensus* among experts, and that variability changes with age, academic level, "I don't know" score or field of study of each expert surveyed. Researchers often apply techniques with which they are familiar and this does not mean that their technique is the best, or even feasible in different environments. Regarding the sampling techniques, some considerations need to be addressed. Visual Census has been applied to beach litter since the 1990s in marine ecosystems and it has been extensively used worldwide also in freshwater environments in the last two decades (Andriolo et al., 2020; González-Fernández et al., 2021; Liro et al., 2023; Gallitelli et al., 2024). Only in the last decade, since rivers are considered to act as plastic litter carriers from land to the sea (Schmidt et al., 2017; Gallitelli and Scalici, 2022), studies about litter in riverine habitats started to be performed (Blettler et al., 2019; Azevedo-Santos et al., 2021). Specifically, floating litter on water and litter on riverbanks have started to be monitored along rivers by using visual census (OSPAR, 2010; Vriend et al., 2020; González-Fernández et al., 2021; Cesarini et al., 2023; Gallitelli et al., 2024).

Regarding drone-based surveys, the highest scores were obtained for beach applications (Fig. 3). Indeed, several publications already proved the suitability of multirotor drones for mapping stranded plastic litter during the last five years (Deidun et al., 2018; Martin et al., 2018; Martin et al., 2021; Gonçalves et al., 2022). Even though some limitations remain in relation to item identification and recognition on aerial images (Martin et al., 2018; Table 1), drone-based techniques applied in coastal environments have been recognized by experts as a valuable solution, also in combination with visual census (Martin et al., 2018). Moreover, the discussion on the harmonization of drone-based data collection is at an advanced step (Gonçalves et al., 2020b, 2022; Escobar-Sánchez et al., 2021; Andriolo et al., 2023; Corbau et al., 2023), and the use of multi- and hyperspectral sensors has the potential to significantly improve automated litter classification and categorization (Gonçalves and Andriolo, 2022; Cortesi et al., 2023).

A few scores regarding applications in the riverine and marine environments (Fig. 3) were counterintuitive and thus this is commented on as follows. Firstly, scores of feasibility, litter detectability and sampling site access were lower for the riverine environment than for the marine systems. Even though applications of drones-based census in marine environments are still more numerous in the literature (e.g., Gonçalves et al., 2022; Andriolo et al., 2023), performing surveys in rivers is generally easier, given that i) monitoring of floating litter on the open sea requires flying the drone from a vessel, and ii) litter items are more detectable on river waters than on the rough sea surface. In fact, wave motion and sun glitter may hamper the detection of litter on the sea surface (Gurbuz et al., 2023), while river waters are generally calmer (Andriolo et al., 2022). It is also noteworthy that the same flight can cover both riverbanks and river flow, allowing a more complete coverage of litter survey in both domains. Secondly, sampling site access and sampling time were valued differently for the three domains in exams, however drone setup and image acquisition do not change significantly across different areas. Finally, the plastic litter removal score was debatable: drone-based surveys can surely support optimized litter collection in the near future, although this application has not been demonstrated yet.

Such controversial scores may be due to opinions given by experts regardless of their lack of direct experience in certain specific techniques.

4.2. Emerging technologies as monitoring tools in high-income countries

Specifically, VC and DC were mainly used in high, medium and low-income countries, while GC and SC were mostly used in high-income countries. However, the absence of information from China, the United States, and Africa could have introduced a bias in our results. We should consider that a large part of the publications comes from these countries as well as a large share of plastic production itself. For both drones and satellites, plastic litter trapped by/under vegetation, semi-buried items and items among wrack and natural wood are difficult if not impossible to spot in visual images (Table 1).

Precisely this is valid only for drones and for freely available satellite images. The main issues remain the low spatial resolution (unless large accumulation of litter occurs) and missing ground-truthing and field validation.

Regarding remote sensing (drones and satellites), feasibility and detectability are still regarded as uncertain by experts working in these topics. In this study, we chose to restrain ourselves to "freely available" satellites and "low-cost" or RGB-only drones. Thus, the comments received are valid for "freely available" satellites, as most research is currently performed with these sensors. Yet, we restrict the comments to multirotor drones mounting RGB sensors, as being cheaper, these are much more used by the research community, despite examples exist of drone applications using more sophisticated multi- and hyperspectral

Table 1
Comparison of advantages and disadvantages of different sampling techniques used in literature and from our survey. VC = visual census, DC = drone census, SC = satellite census, GC = GPS/GNSS litter tracking systems census.

Sampling technique	Literature results		Our survey results		References
	Advantages	Disadvantages	Advantages	Disadvantages	
VC	Medium cost for small sampling sites. Globally employed.	Limited sampling site access, time-consuming, and expensive for large areas.	Litter census feasibility and detectability.	Sampling site access and long sampling time.	OSPAR Commission, 2010; González-Fernández and Hanke, 2017; van Emmerik et al. 2018; Vriend et al., 2020; UNEP, United Nations Environment Programme, 2020; Hurley et al., 2023; Gallitelli et al., 2024.
DC	Not invasive, high-resolution imagery, coverage of large and remote areas.	Limited battery autonomy.	Efficient sampling site access, allow systematic surveys, high resolution images/GSD.	Litter removal, constraint by logistics and use prone to favorable weather conditions or item visibility on images.	Geraeds et al., 2019; Garcia-Garin et al., 2020b, 2021; Andriolo et al., 2023
SC	Global area coverage.	Free-to-access data can be of a suboptimal spatial resolution (~10 m pixels), commercial data can be of a high-cost, impact from clouds, and validation is work in progress	Sampling site access.	Litter detectability and removal. Dependent on image quality. Only relatively-large litter accumulation patches.	Kataoka and Nihei, 2020; Topouzelis et al., 2021; Garaba and Park, 2024, Cózar et al., 2024
GC	Span remote areas.	Limited usability range due to GPS, limited spot and characterization of plastic litter types.	Litter detectability.	Litter feasibility, detectability, removal, sampling site and time.	Tramoy et al., 2020; Tran-Thanh et al., 2022; Boon et al., 2023; Mani et al., 2023.

sensors (Gonçalves and Andriolo, 2022). Notwithstanding there are several conditions which must be favorable to use satellites (especially free-of-charge images, with Sentinel 2), however ground-truthing is still limited for satellites while for drones it has been achieved to a greater extent (Table 1). In our questionnaire, scores are quite high despite to date, only a few works showed the possibility of surveying litter from space. Considering "detectability", for satellites, there is an enormous difference between detecting floating or terrestrial litter partly due to the difference in the image background (Lavender, 2022). For floating litter, satellite-based detection mainly relies on proxies which are most useful in highly polluted waters (Cózar et al., 2021, 2024; Topouzelis et al., 2021; Booth et al., 2023). Indeed, the low spatial resolution of satellite data, does not allow to detect small plastic items dispersed in marine and terrestrial environments.

On land, limited research has been conducted and is available, with examples using Copernicus Sentinel and commercial data sources (Kruse et al., 2023; Lavender, 2022). On the other hand, drones, are commonly used for monitoring litter on highly dynamic coasts and rivers, however image resolution is pivotal for item detection and classification (Andriolo et al., 2023). It is expected that both these techniques will be rapidly improved in the future, allowing for better monitoring in aquatic and terrestrial systems. Cutting-edge technologies could improve our ability to detect plastics trapped in riverine systems (Koutalakis et al., 2023). Therefore, apart from the riparian zone and beach/coast systems, future research could employ GPS/GNSS tools and underwater drones (e.g., ROVs) to quantify submerged litter on the river/ocean bottom and in the water column.

As a future perspective, it is essential to improve monitoring methods or create new ones where there is lack of data (i.e., remote regions). Deep oceans, shelf sediments, remote terrestrial lands, and river water column contain large stocks of waste in their mass balance of the global plastic cycle, but the first two are currently almost impossible to monitor on a reasonable scale (Cózar et al., 2024; Gallitelli and Scalici, 2024). In both rivers and oceans, what is under the surface water is still largely unseen and difficult to be spotted and quantified (Sonke et al., 2022).

4.3. *Towards an optimized and integrated monitoring methodology*

When selecting the most appropriate sampling technique, we should consider that visual census allows researchers to survey plastics at specific times – depending on the main goal and in addition to provide time series measurements when surveys are repeated. For instance, when applying the OSPAR guidelines that require coverage of 100 m land-strips, it might take several hours and a large group of people to sample plastic litter on a beach with relatively high time requirements and logistic costs (OSPAR Commission, 2010; Vriend et al., 2020; Galgani et al., 2023; Gallitelli et al., 2024). The advantages of visual census against other techniques are the high level of detail and the exact characterization of litter types and categories when the surveys are performed by well-trained observers. On the other hand, drones can provide rapid flight times and can be coupled with automated image processing but generally provide lower detail to identify litter categories than with visual census (Geraeds et al., 2019; Andriolo et al., 2022). Moreover, drones can offer more time-efficient solutions. Especially, with preprogrammed mission planning drones are capable of delivering high-pression maps that can be repeated multiple times over to yield high-resolution time-series (Kvile et al., in review). Visual census also enables comparability with OSPAR methodologies, facilitating repeated surveys at the same location without dependence on drone operations, image acquisition and processing, or weather conditions (Table 1). Satellites do not directly detect plastic litter but only accumulation patches (Garaba and Park, 2024; Cózar et al., 2024). Both drones and satellites allow for quick acquisition of images; however, subsequent data processing, including manual processing and the selection of training samples for automated processing remains time-consuming and is still undergoing validation. For comparison purposes, drones have a high value for "litter detectability" (due to their higher image resolution, i.e. GSD) in comparison with satellites, but a lower "level of details" in comparison with the visual census. The level of detail provided by drone-based surveys can vary significantly based on the expertise of operators, image quality, and/or automated technique capability.

To progress and provide fast and reliable litter surveys with global coverage, future protocols and guidelines should propose affordable monitoring techniques allowing a global assessment of plastic pollution, especially in regions which are currently unsurveyed. Given that the analytical cost of different monitoring methods varies from very expensive remote sensing tools to low-cost visual census (depending on the salary level for human labor in the specific country and regions, Table 1), there is a disparity between techniques that can be used by high- and low-income countries with limited budgets for research. As more data on plastic litter in aquatic and terrestrial systems are needed to better understand litter accumulation and fate, monitoring guidelines should preferentially consider low-cost methodologies. Satellite observations can be costly compared to visual surveys and low-income countries are often not able to access the same technologies available to high-income countries. For instance, the time required to perform visual census is extensive, ultimately limiting the spatio-temporal coverage of the monitoring. Based on a specific aim, comparable large-scale field surveys are generally more expensive than using satellite images. Drones are nowadays cheaper for high-income countries than in the past but they can still be expensive for low-income countries, especially if compared to visual surveys. Low-resolution satellite imagery is freely available on a global scale, on the other hand, highly qualified experts and high-performance computing resources are required for data processing. Therefore, low-income countries with low funding budgets could have challenges in using satellite images or drones if they do not receive external support.

The analysis of the relationships among the use of different monitoring methods in different countries deserves further in-depth studies. Indeed, the country-technique relationships may depend on a large number of variables, and it is not only related to costs (e.g., also by domain: floating or stranded, area extent, used devices, personnel and instrumentation availability and so on), since the choice of using a certain technique is not only driven by economic issues, but also logistic, expertise, and research purposes. Another problem for all three remote sensing methods is the high cost (e.g., financial, environmental etc) and lack of trained people and infrastructure for computer data processing and storage. This leads to a high vulnerability of large datasets, especially if images. Also, if the origin of the plastic litter data is not traceable back to its image, it lowers its credibility.

Although the data compilation method and the questionnaire used here are a cost-effective and fast method to assess the suitability of a given sampling protocol, some limitations might be pointed out. Firstly, only 46 people from the plastic community responded to the questionnaire, therefore this could be considered as a first attempt to review and assess the litter sampling technique topic. Secondly, the geographical distribution of participants seems to have a limited spatial coverage, as respondents were not coming from not all continents. This could have introduced a bias in our results, given that participants from countries where plastics are mainly produced and disposed of are not fully represented. Thirdly, regarding the questionnaire, relatively few questions regarding the limitations of the approaches were asked. However, the experts evaluated each method according to their own knowledge of the sampling technique they used more commonly and the final score was corrected for the "unknown" sampling techniques.

4.4. Increasing role of AI for future monitoring of plastic litter?

All monitoring methods and sampling strategies have several advantages and limitations, which may lead to a misinterpretation of litter detection (Jia et al., 2023). The use of AI in marine litter research has already indicated that automatic classification, object detection and segmentation of macroplastic litter is feasible and litter assessment with AI can be achieved (Politikos et al., 2023). Regarding the use of artificial intelligence to detect plastic litter, machine learning allows to save a considerable amount of time compared to traditional visual counting methods. In fact, AI can boost image analysis and make automated litter detection possible at larger spatio-temporal scales (de Vries et al., 2021; Cózar et al., 2024), ultimately allowing the development of more effective targeted clean-up and mitigation actions. During our survey, researchers indicated that they would choose to use AI only after careful method development and validation. In addition, our experts highlighted that results provided by AI should be always supervised by human operators. By carrying out a good feedback process with field results before using artificial intelligence, the analysis time of several censuses could be automated in less time, once the required time is invested to train the AI algorithms. While for drones it might be a feasible task to develop machines and deep learning techniques at local and regional environmental conditions, the complex challenge is to have something universal to be used for global litter monitoring (Gonçalves et al., 2020a; Garcia-Garin et al., 2021). The standardization is tricky as similar image resolution from every survey could be needed (Andriolo et al., 2023) especially when trying to develop an algorithm able to identify the almost infinite variety of litter typologies in different environments and habitats, for which a great number of training images are needed (Gonçalves et al., 2020a; Garcia-Garin et al., 2021). For satellites, it is pivotal to distinguish between floating and terrestrial litter (Topouzelis et al., 2019; Biermann et al., 2020; Tasseron et al., 2022). Ground-truthing validation is challenging but essential, and in general, the real problem is figuring out what is inside a specific pixel, for instance, a 10 × 10 m satellite image pixel. In this regard, dedicated satellite missions specifically aimed at litter detection would be key to improve our monitoring capabilities (Cózar et al., 2024; Garaba and Park, 2024). In conclusion, the operational use of AI-marine litter studies still needs additional development and testing before offering interesting opportunities to stakeholders.

5. Conclusions

Detecting the so-called "missing plastics" (here "land-retained plastics", i.e., litter transported by rivers not reaching the sea) in aquatic and terrestrial ecosystems is key to understanding their accumulation, fate, and effects on ecosystems. Such information is essential for the effective management and limitation of "missing plastics" expansion in natural ecosystems. Through a questionnaire submitted to experts distributed across different continents and research experiences, this paper gave a general overview of different opinions and perceptions regarding the suitability of four different monitoring techniques used to monitor macroplastic litter in riverine, marine and coastal environments. Visual census, drone, satellite and alternative solutions were evaluated based on their feasibility, litter items detectability, site accessibility, performance time and litter removal capability. Overall, visual census and drones surveys obtained the highest scores, given that these two techniques have been already implemented worldwide during the last decades. Satellites monitoring obtained the lowest scores, as limitations in spotting plastic litter from space are still significant, and ground-truthing is sparse. Other alternative methods also obtained low scores due to the limited applications and low level of knowledge by the experts surveyed. To further support the global monitoring effort of plastic litter in different environments, given that plastic research is still growing, the development of new and more efficient methods is still needed and should be a priority. Thus, the outputs of this review might be (1) used as a starting point for early career scientists approaching these topics and (2) transferred to researchers, citizens, and stakeholders involved in training activities - considering that monitoring actions are important to effectively mitigate the plastic pollution problem.

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CRediT authorship contribution statement

L. Gallitelli: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **P. Girard:** Writing – review & editing, Visualization, Validation, Supervision, Methodology. **U. Andriolo:** Writing – review & editing, Visualization, Validation, Supervision, Methodology. **M. Liro:** Writing – review & editing, Visualization, Validation, Methodology. **G. Suaria:** Writing – review & editing, Visualization, Validation, Methodology. **C. Martin:** Writing – review & editing, Visualization, Validation, Methodology. **A.L. Lusher:** Writing – review & editing, Visualization, Validation, Methodology. **K. Hancke:** Writing – review & editing, Visualization, Validation, Methodology. **MCM Blettler:** Writing - review & editing, Visualization, Validation.**O. Garcia-Garin:** Writing – review & editing, Visualization, Validation. **I.E. Napper:** Writing – review & editing, Visualization, Validation. **L. Corbari:** Writing – review &

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Declaration of competing interest

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

Data availability

All data are present in the manuscript and Supplementary Materials.

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Ethical Statement

The questionnaire did not need ethical approval because all personal information about the involved researcher has been deleted and handled according to the general GDPR regulations (https://gdpr.eu/). Moreover, all respondents to the survey were later invited to be co-authors of this manuscript.

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