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Microplastics in the marine environment: development of a new citizen science tool

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ABSTRACT

Microplastic pollution poses a global threat to all marine ecosystems, and citizen science provides a valuable method for monitoring its presence and distribution. However, volunteers lack access to costly and complex laboratory techniques, such as Raman and FTIR spectroscopy, for accurate identification of microplastics. The purpose of the study was: 1) to develop a simple, low-cost, and field-adaptable protocol that allows volunteers to identify and quantify microplastics by distinguishing them from organic matter and non-plastic materials based on their melting behaviour, and 2) to examine the polymer composition. A dedicated support tool and thermal verification method were developed and tested in the laboratory before field trials. Samples were collected with a Manta net during the 2024 and 2025 Expedition MED campaigns in the Mediterranean Sea, followed by wet sieving, visual characterisation, and thermal deformation analysis. The identification error rate was determined by measuring the proportion of visually selected particles that failed to melt during the thermal verification. Trials involving 39 volunteers showed that the melting verification method effectively reduces misidentification, thereby decreasing the overestimation of microplastic particles. In the 2024, 926 were tested with a 4.6% error rate. By comparison, the 3,421 particles tested in 2025 yielded a higher error rate of 8.8% due to a much higher concentration of microplastics and a greater proportion of particles in the smallest size classes (e.g., < 2.5 mm). Citizen scientists from diverse socio-demographic backgrounds successfully applied the protocol in the field after a mentored training, demonstrating that volunteers can contribute meaningfully to both the collection and analysis of microplastics by providing accurate results comparable to laboratory research. Overall, this approach offers a reliable and accessible method to improve data quality in citizen science microplastics research.

1. Introduction

Plastic pollution is a significant global issue observed across all environments, ranging from soil (Chae and An, 2018) to ocean depths (Zhu et al., 2024) and the atmosphere (Allen et al., 2022). Since the 1970s, global plastic production has increased from 47 million tons to over 400 million tons in 2022 (Anon, 2023), and 79% of this has not been effectively managed (Liu et al., 2025), resulting in environmental accumulation. Plastic debris may persist for decades or even centuries (Chamas et al., 2020), degrading through mechanical, chemical, and biological processes that vary in intensity depending on the plastic's chemical composition (Corcoran, 2022). This degradation causes the plastic to fragment into smaller particles, reaching the size fraction of microplastics (MPs; 1 to 5000 μm (Gesamp, 2016)) of various shapes, colours and polymeric compositions, and which are then found across all environments, from urban areas (Setälä et al., 2022) to every marine habitat (do Sul and Costa, 2014).

Within this global context, the Mediterranean Sea is one of the most polluted seas, with approximately 0.31 million tons of plastic waste entering per year (850 tonnes/day; Segur and Sonke, 2025). This high level of pollution results from the combination of its semi-enclosed geography and intense human activity, including high population density, fishing, and tourism (Cincinelli et al., 2019). Some studies have shown that polyethylene (PE) and polypropylene (PP) are the most common polymers identified in the surface of the Mediterranean Sea, as their low density allows them to float, while denser polymers such as polystyrene

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(PS), polyvinyl chloride (PVC), polyamide (PA), and polyethylene terephthalate (PET) tend to sink (Guo and Wang, 2019; Kedzierski et al., 2022). MPs studies at the sea surface have been conducted primarily on the northern part of the Mediterranean Sea, but significant knowledge gaps remain in the southern region (Terzi et al., 2024), with fewer to no data available in countries like Morocco, Tunisia, Algeria, Libya and Syria (Chatziparaskeva et al., 2022).

Citizen science offers an important approach to addressing this imbalance. Involving local communities in sampling and monitoring allows access to under-sampled locations and helps establish long-term monitoring, especially where scientific resources are limited (Catarino et al., 2023; Ershova et al., 2021; Hidalgo-Ruz and Thiel, 2015; Jones et al., 2025). Moreover, involving the public in science projects contributes to greater awareness of MP pollution, including the environmental impact and health risks (Dowarah et al., 2022; Garcia-Vazquez and Garcia-Ael, 2021). This engagement can also lead to the development of practical actions and future solutions, including community initiatives and policy changes (Hossain, 2024; Li et al., 2025).

Citizen participation in scientific research has primarily focused on reporting the distribution and composition of macro- and meso-plastics found on beaches and along coastlines (Hidalgo-Ruz and Thiel, 2015). In contrast, MPs studies involving citizen science concentrate on beaches and within sediments (Carbery et al., 2020; Nel et al., 2020; Pasolini et al., 2023; Walther et al., 2024), when compared to surface waters (De Haan et al., 2022; Setälä et al., 2022).

Nevertheless, concerns have been raised about the reliability of citizen science results (Aceves-Bueno et al., 2017; van der Velde et al., 2017), highlighting the importance of verification procedures to minimise error and enhance data quality. A major issue arises during the visual identification of MPs, whether performed by the naked eye or using a stereomicroscope, as the wide variety of shapes and colours, in addition to the extend of particle degradation, can lead to underestimation or overestimation of results (Song et al., 2015). To address this, most previous citizen science projects have limited volunteer involvement to sample collection, with all further analyses conducted later in laboratories by researchers.

In the laboratory, several advanced analytical techniques are employed. Spectroscopic methods, including Fourier Transform Infrared (FTIR) and Raman spectrometry, are widely used to detect MPs based on their chemical composition (Dong et al., 2023). Fluorescence staining methods using dyes like Nile Red (NR) or Idye Pink are also applied, providing additional visual detection. Thermal analysis offers an alternative approach by identifying MPs through heat degradation, which causes the transition of MPs from a solid to a liquid state. Thermal techniques can either provide detailed compositional information, such as pyrolysis gas chromatography with mass spectrometry (py-GC/MS; (Peñalver et al., 2020) and differential scanning calorimetry (DSC; (Lee et al., 2024), or serve as rapid visual detection methods, as in the case of the hot needle test (Beckingham et al., 2023).

All these advanced analytical techniques are effective in controlled laboratory conditions. But their high cost (Ribeiro et al., 2024), time requirements (staining can take from 30 minutes to two days) (Shruti et al., 2022), reliance on specialised equipment, and need for experienced operators make them unsuitable for use in citizen science projects.

To overcome these limitations, this study proposes an alternative approach that combines visual identification with a simplified thermal technique, building on the method previously explored by Kedzierski et al. (2021). This allows participants to directly verify their observations in the field. This combination ensures that volunteers are not excluded from the analytical process, while enhancing data reliability. To our knowledge, such a field-based protocol has never been implemented in citizen science MPs research.

The aim of this project was to develop a simple, low-cost and field-adaptable protocol suitable for citizen science to identify and quantify MPs by distinguishing them from organic matter based on their melting temperature. In particular, the objectives were: 1) to design and create a dedicated support tool for sample handling, 2) to develop a heating confirmation technique using controlled time and temperature exposure based on preliminary laboratory tests, and 3) to test the complete protocol under field conditions with volunteers from various environmental associations.

2. Materials and methods

2.1. New experimental ceramic support development

2.1.1. Design and fabrication

The colour, pink, was chosen for the development of the new experimental support. This colour is less observed in the sea and increases the visibility of transparent and white particles (Martí et al., 2020). The clay plate was manually moulded using pink-firing clay (Solargil®) to form a 70 x 70 mm flat square that was 5 mm thick. Cavities were carefully pressed into the surface using a 3-D printed stamp, built with SolidWorks (Howard, 2008), to create uniform cavities (2 mm depth) for sample placement (see .STL files in the supplementary materials). This structure enables the simultaneous analysis of 105 MPs. After moulding, the clay plates were left to dry at room temperature for 48 hours, then fired in a furnace (Nabertherm LHT 08/16) following a controlled temperature program. The firing process started at 0 °C and proceeded to 110 °C at a heating rate of 100 °C/h, with a residence time of one hour. The temperature was then increased in two successive steps: from 110 °C to 600 °C and from 600 °C to 1000 °C, each with a heating rate of 200 °C/h and a residence time of one hour. These heating stages are fundamental to the ceramic processing, involving dehydration of water molecules, carbonisation of organic matter, and finally the vitrification process, which reduces porosity and increases mechanical strength (Dong et al., 2021; Johnson et al., 1988). This ensures the ceramic plates are sufficiently robust to withstand repeated thermal heating.

2.1.2. Thermal behaviour of the ceramic support

To evaluate the thermal behaviour of the ceramic plates under the conditions used during the MPs melting experiments, the heat transfer between the heating source and the new support was measured using three thermocouples (TC-08 Data Logger) and three different ceramic plates. The thermocouples were placed at the centre and on the right and left extremities of the ceramic plate. The temperature was recorded every 30 seconds over a 30 minutes heating period to determine the time required to reach 200 °C, which encompasses the melting temperatures of PE and PP (Callister Jr and Rethwisch, 2020).

Additionally, the thermal distribution across the plates was recorded using a thermal imaging camera (FLIR). Four ceramic plates were placed on a 50 x 50 cm electric heating plate (Fisherbrand™ Isotemp™ Aluminium-Top Hotplate) that had been preheated to 200 °C, and a thermal video was recorded for five minutes. This procedure was repeated two times, resulting in a total sample size of 8 ceramic plates analysed.

2.1.3. Calibration of the fusion method

2.1.3.1. Microplastic sample collection. In the aim to validate key parameters of the protocol, such as the optimal temperature and duration of the heat exposure, MPs were used to perform first steps of laboratory experiments. MP particles were collected at the beach of Guidel Plage, South Brittany, France (47.76802 °N, 3.52923 °W) in March 2025. Their chemical composition was determined using an Attenuated Total Reflection Fourier Transform Infrared spectrometer (ATR-FTIR Vertex70v, Bruker). All spectra were recorded in the absorbance mode in the 4000 – 600 cm^{-1} regions with 4 cm^{-1} resolution and 16 scans. Each particle was placed onto the germanium diamond cell (ATR Golden Gate) to be analysed (Kedzierski et al., 2019). The obtained spectrum was compared with the reference spectrum from the study of Kedzierski et al. (2022) to identify the polymer composition of the MP particles. Since PE and PP particles constitute the bulk of the MPs collected in the ocean surfaces (Cincinelli et al., 2019), MPs belonging to these chemical categories were selected for the next tests.

2.1.3.2. Validation of melting temperature using DSC. Differential scanning calorimetry analysis was performed to determine the exact melting temperature of MPs, to complement the observations from the visual melting experiment, and to assess potential differences between pure and environmentally degraded particles. A Mettler Toledo DSC3 was used to obtain the melting temperature (Tm) of two pure and four environmental PE and PP particles (mean PE = 6.5 ± 0.3 mg and mean PP = 6.2 ± 0.3). Each particle, weighing approximately 6 mg, was placed in an aluminium crucible. Measurements were carried out under N_2 atmosphere at a flow rate of 50 ml/min and a temperature gradient from -50 °C to 200 °C with a heating rate of 10 °C/min.

2.1.3.3. First melting test: beach microplastics. A melting experiment, with a heating plate, was conducted to precise the optimal melting temperature. For each polymer (i.e., PE and PP), 15 MP fragments from Guidel Plage beach with different colours, measuring 3.87 ± 0.67 mm, were placed individually in a cavity of the ceramic plate to be photographed in a lightbox (Havox® HPB-80D). The camera (Nikon D850, AF-S VR Micro-Nikkor 105 mm f/2.8G IF-ED, ISO: 100, aperture: f/3.2, shutter speed: 1/80) was placed above the lightbox and fixed to a copy stand (KAISER RS2 XA Copy Stand, 40x50 cm). Then, the ceramic plates were placed on an electric heating plate to be heated. Starting at 130 °C, corresponding to the melting temperature of PE (Callister Jr and Rethwisch, 2020), the temperature was increased in 10 °C intervals up to 220 °C. At each temperature, the ceramic plate was held for 20 minutes before being photographed. With all the images obtained, the MPs surface area was measured using ImageJ/FIJI software (Schindelin et al., 2012) to calculate the deformation difference at each temperature.

2.2. Pre-field trial: application of the melting test to Mediterranean microplastics by citizen scientists under laboratory conditions

2.2.1. Sampling of microplastics

Surface water was sampled in the Northeast Mediterranean Sea as part of the participative science activities of the Expedition MED association (www.expeditionmed.eu) from July 1st to 24th, 2024. A total of 10 samples were collected for this experiment using a 330 µm mesh size Manta trawl, with a rectangular net opening measuring 60 cm × 20 cm (Fig. 1). Sampling was conducted under calm conditions, with a sea state of 1 to 2, and wind force between 0 and 2 on the Beaufort scale. The net was towed at an average speed of 2.625 ± 0.3 knots for 30 minutes. A propeller flowmeter was attached to the opening, and the average filtered volume of each manta trawl was 318.50 ± 35 m^3. Between each sample, the manta trawl was rinsed with environmental water. The samples were then transferred to plastic jars and preserved in a 50/50 (v/v) water/ethanol mixture to be sent later to the Institut de Recherche Dupuy de Lôme (IRDL, Lorient, France) for analysis.

2.2.2. Extraction and characterisation

Collected MPs samples were first wet sieved to separate the particles according to their size class. A stainless-steel sieving cascade with four different mesh sizes was used (> 5mm, 2-5 mm, 1-2 mm, 0.315-1 mm) (Hidalgo-Ruz et al., 2012). Wet sieving was performed under a fume hood with 3 L of distilled water. Particles, corresponding to 2-5 mm and 1-2 mm were then counted and classified under a stereomicroscope (Stemi 305, Carl Zeiss) according to their shape and colour, where 0.315-1 mm particles were stored in Petri dishes with distilled water for future analysis. Each Petri dish was photographed for particle measurement using ImageJ/FIJI, and all particles of each sample were weighed using an analytical balance (XS205DU, Mettler Toledo). Furthermore, the chemical composition of 112 particles was determined by ATR-FRIR, as previously described.

To minimise contamination risks, a clean 100% cotton laboratory coat and nitrile gloves were worn, and synthetic clothing under the coat was avoided. The working station and all equipment were cleaned with distilled water, ethanol and/ or acetone. The sample holder for FTIR analysis was cleaned after every 10 measurements. Samples were kept covered with aluminium foil. Non-plastic materials (steel and glass)

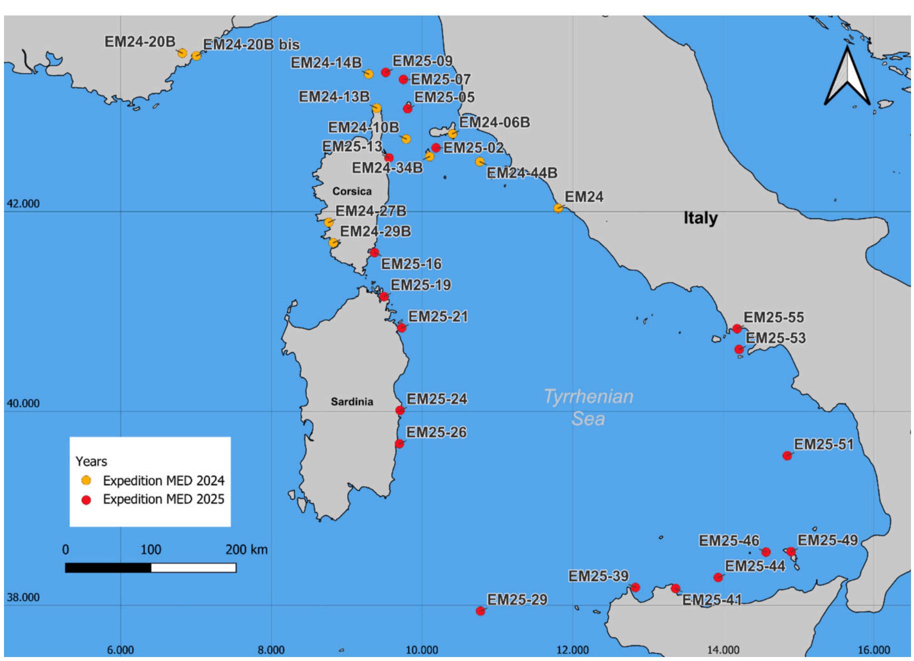

Fig. 1. Map of the Northeast Mediterranean Sea showing the location of the sampling stations during the 2024 and 2025 campaigns of Expedition MED.

were used, a laboratory procedural blank was performed, and the only contamination particles detected were from the sponges used to clean the materials.

2.2.3. Heating and image analysis

For each sample, the number of particles identified by the volunteer as potential MPs was counted (N). To reduce the workload of the verification process and speed up the analysis for the volunteer, a subsampling approach was applied. For samples containing more than 100 particles, the number of MPs to be verified through the melting verification process was determined using equations adapted from Kedzierski et al. (2019) (Supplementary method S1 and table S1).

For each sample, particles were manually placed into individual cavities of the ceramic plate using a metal tweezer. The ceramic plate was photographed before heating, then placed on a preheated plate at 200 °C for 20 minutes. During the melting verification, care should be taken to avoid inhaling any fumes generated. From this perspective, we recommend working in a well-ventilated area and avoiding staying in the immediate vicinity during the heating process. Working under a fume hood, if available, or wearing a respirator suitable for solvent vapors should also be considered. Moreover, particles should be handled carefully to prevent dispersion by wind under outdoor and onboard conditions. Particle deformation was visually observed and noted at 5, 10, 15 and 20 minutes to record the progression of melting particles. After heating, the ceramic plate was removed, allowed to cool to room temperature, and then placed back in the lightbox for photography. The two images obtained (i.e., before and after heating) were analysed with Fiji software to confirm the visual observation of the total melting particles.

2.3. Citizen science implementation

The protocol method developed in laboratory conditions was tested in field conditions with citizen science. Volunteers were provided with the same material used in the laboratory, support documents and a datasheet to ensure data quality (Hidalgo-Ruz and Thiel, 2015). The support documents included (i) a simplified and straightforward protocol guideline, (ii) a photo identification guide of the MPs shape category, and (iii) a sheet to report the results. Before the experiment, a demonstration of the several steps was presented to ensure standardisation.

After the end of each trial, a survey was created to collect participant information and identify potential improvements to the protocol. The survey includes two open-ended questions and thirteen closed questions, organised into four main categories: socio-demographic data, experience, motivation, and protocol difficulties (Supplementary Table S2).

2.3.1. Pre-field trial with local association

A preliminary field trial of the protocol, with the participation of 11 volunteers from Objectif Dune, Observatoire du Plancton and Les Mains dans le Sable associations, was carried out at Gâvres, South Brittany, France (47.69662 °N, 3.35308 °W) in May 2025. The purpose was to implement the protocol with volunteers for the first time, identify potential difficulties, and evaluate steps for improvement before the final trial. For this analysis, volunteers were provided with six prepared samples (Table 1), each consisting of distilled water containing a controlled concentration of MPs and natural organic and inorganic particles. The MPs collected at Guidel Plage beach (see Section 2.2.1) were individually measured and classified according to their morphometric characteristics. Additional natural materials, including algae, driftwood and shell fragments, were incorporated to stimulate realistic field conditions.

2.3.2. Final field trial with expedition MED

The final field trial of the protocol was performed from July 5th to the 8th of August, during the 2025 campaign organised by the Expedition MED association, with 19 samples collected and analysed by 28 volunteers (Fig. 1). Sampling followed the methods described in Section 3, with a towing speed of 2.94 ± 0.4 knots under moderate sea conditions (wind force 3, sea state 3). A minor adjustment was made to the sieve size classes, using 2.5 - 5 mm and 1 - 2.5 mm instead of 2 - 5 mm and 1 - 2 mm.

Table 1
The content of each prepared sample includes controlled concentrations of microplastics, as well as natural organic and inorganic particles (GP = Guidel Plage beach)

Sample	MPs (count)	PE abundance	PP abundance	Natural material (count)
GP25 - 01	10	7	3	10
GP25 – 02	10	6	4	100
GP25 - 03	50	39	11	50
GP25 - 04	100	64	36	10
GP25 - 05	100	72	28	100
GP25 - 06	50	32	18	10

2.4. Data analysis

The data were presented as means ± standard errors. Before analysis, data were tested for normality and homogeneity. Pairwise Wilcoxon tests were performed to find the optimal melting temperature for two different polymers, as well as to examine the temperature distribution within each ceramic plate (intra-plate) across five spatial locations (bottom right, bottom left, centre, top right, top left). To compare differences between plates (inter-plate) at each spatial location, Kruskal-Wallis tests were conducted across the eight ceramic plates.

To assess volunteer identification accuracy, particles were categorised on their response to the melting verification method as follows:

True positive (TP): Particle identified as microplastics by volunteers and confirmed as plastic (i.e., melted during the test).

False positive (FP): Particle identified as microplastics by the volunteer and not confirmed (i.e., did not melt).

During the preliminary field trial, the initial quantity of MPs in each sample was known, allowing the calculation of false negatives (FN), defined as particles identified as non-MPs by volunteers but were truly plastic. True negatives (TN) were defined as particles identified as non-MPs but confirmed to be non-plastic.

In contrast, for the 2024 and 2025 Expedition MED samples, false and true negatives were not considered, as only particles identified as MPs by volunteers during sorting were retained for analysis.

An error *rate* was then calculated as the proportion of false positives relative to all particles identified as MPs by volunteers:

$$error\ rate = \frac{FP}{TP + FP} \times 100$$

where $TP + FP$ corresponds to the total number of particles initially identified as MPs by the volunteers. To account for subsampling (see Section 2.3.3) in the samples listed in supplementary Table S1, a scaling score was calculated to estimate the total number of true particles analysed. The scaling score was defined as the ratio between the total number of particles identified as MPs (N) and the subsampled particles (n) analysed for the melting verification:

$$Scaling\ score = \frac{N}{n}$$

When all particles in a sample were verified and no subsampling was applied, the scaling score was equal to 1. For subsampled cases, the number of adjusted MPs was then estimated by dividing the number of particles confirmed by melting (TP) by this scaling score:

$$Adjusted\ MPs = \frac{TP}{Scaling\ score}$$

This adjustment ensured that verification results were representative of the full sample.

A Kendall correlation tests were performed to examine differences in mean false positives relative to the initial abundance of particles identified as MPs. Wilcoxon tests (for non-parametric data) and t-test (for parametric data) were conducted to assess differences in mean false positives across the size classes. All statistical analyses were performed using R 4.3.2 (R Core Team, 2020), with $\alpha = 0.05$ to assess statistical significance.

3. Results

3.1. Protocol optimisation

3.1.1. Optimal temperature and time exposure

The average melting temperature measured using DSC, ranged from 108 °C to 158 °C for PE particles collected on Guidel Plage beach, while that of PP was between 165 °C and 169 °C. These values closely aligning with those of the scientific literature (Lynch et al., 2024; Majewsky et al., 2016; Sorolla-Rosario et al., 2022) and highlighting that, on this particular aspect, few differences exist between environmental and reference samples. The deformation of MP particles of PE and PP investigated under increasing heat to determine the melting temperature of both polymers demonstrate the same global pattern. The surface deformation of the PE particle begins at lower temperature (Fig. S1a), with statistically significant deformations observed between 140 °C and 150 °C, and between 150 °C and 160 °C ($p = 0.02$ and $p = 0.04$, respectively). After 160 °C, particles have reached their maximum deformation, with no further changes observed. In comparison, PP particle alteration begins at higher temperatures (Fig. S1b), with statistically significant deformation between 180 °C and 190 °C ($p = 0.04$). Importantly, none of the polymer samples tested exhibited melting temperatures above 200 °C. This temperature was therefore chosen as the maximum temperature for the melting protocol.

Pairwise Wilcoxon tests revealed significant differences ($p < 0.05$) between intra-plate locations, indicating heterogeneity in temperature distribution. For example, at 30 minutes, the mean temperature recorded on the three ceramic plates tested was 190 ± 11 °C, as measured by the central sensor. The right sensor reached 188 ± 21 °C, while the left remained lower at 174 ± 8.1 °C (Fig. 2). On average, the centre position is 8.55 °C warmer than the edges. Moreover, Kruskal-Wallis tests also showed highly significant inter-plate differences ($p < 0.001$) across all locations indicating strong variability between plates. These variations in temperature distribution, observed both within individual ceramic plates (intra-plate variations) and between different plates (inter-plate variations), reflect the irregularities inherent in the artisanal manufacturing process of the ceramic support.

Despite these irregularities, all MPs melted within 20 minutes (Fig. 2). All PE particles melted rapidly within 5 minutes, while PP particles melted after, requiring between 8 and 16 minutes to melt. These results indicate that the temperature reached was sufficient to exceed the melting points of both polymers. Therefore, a heating duration of 20 minutes at 200 °C is adequate to ensure complete melting of PE and PP particles.

3.2. Laboratory protocol validation: application to expedition MED samples (2024)

Plastics were found in all samples (n = 10) from Expedition MED (year 2024). A total of 926 particles visually identified as potential MP were collected. Plastic's abundance per sample varied from 6 to 320 particles, where the size range 1-2 mm was the most abundant (64%), followed by those in the 2-5 mm range (30%) (Fig S2a). The predominant shape category across all samples was fragment, accounting for an average of 50.4%, followed by film (38%), filament (7.4%), and foam (4%) (Fig S2b). Filaments were present in all samples except one. Eleven colours were noted, with two new colours added (pink and grey), while transparent was the most common colour (54%), followed by white (21%). Other colours accounted for less than 10% (Fig S2c). A total of three distinct polymers were identified through ATR-FTIR analysis: PE and PP were the most abundant polymers (64% and 30%, respectively), followed by PS (6%) (Fig S2d).

All particles identified as potential MPs were tested through melting protocol to validate their identification. As a result, 883 particles melted

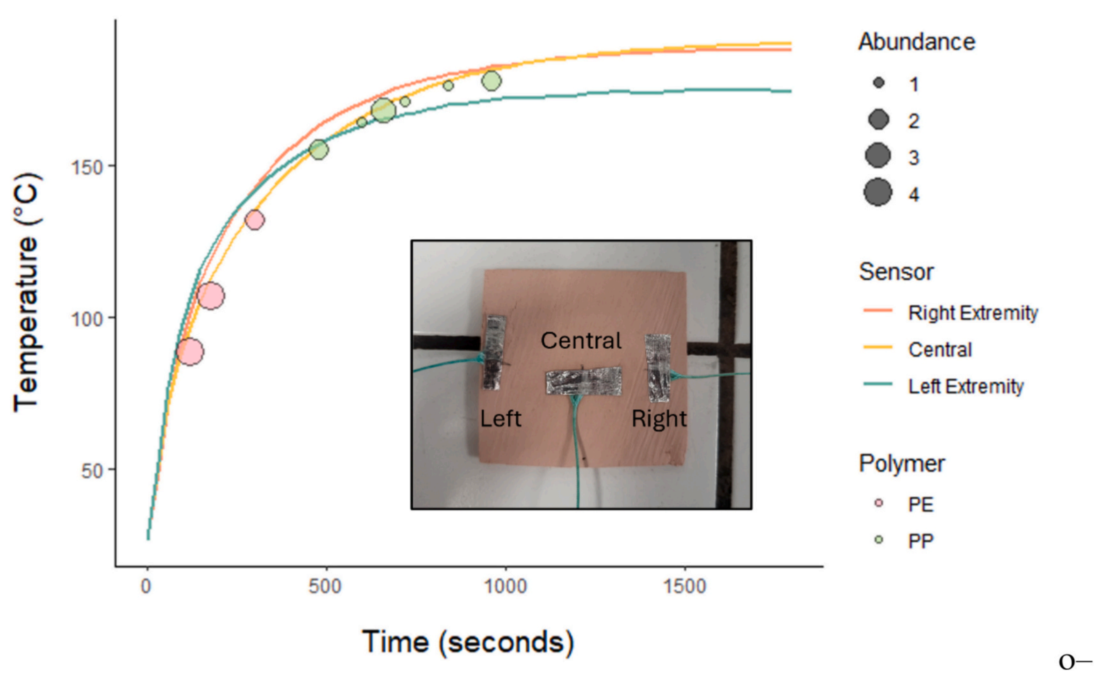

Fig. 2. Thermocouple temperature measurement with three different sensors (central, right and left extremities) on the ceramic plate and melted MP detection of two polymers (n = 10 for PE and n = 10 for PP) over time.

and 43 remained unmelted, indicating the presence of visual misidentifications resulting in an error rate of 4.64% (Fig. 3).

Of the remaining 43 particles, some (46.5%) were visually identified as organic debris. These particles showed no visible deformation or colour change, suggesting a misidentification during the initial sorting process, potentially due to their similarity in shape and colour to the other MPs.

Another portion corresponded to MPs (53.5%) that were visually noticeable due to a small colour or size change. Most of these unmelted MP particles were black fragments and transparent films. Their persistence is likely due to insufficient contact with the heated ceramic surface, which limits heat transfer and prevents complete melting.

Regarding the size class, the mean error rate for 2-5 mm was 0.06 ± 0.08 and for 1-2 mm was 0.04 ± 0.04, with no significant difference between groups ($W = 55$, $n = 20$, $p = 0.72$). Similarly, no significant difference was found between the error rate and particle abundance ($Z = 0.03$, $n = 20$, $p = 0.067$), ranging from 0% in the lowest particle sample and 0.04% in the highest abundance sample.

Most particles (66%) melted within the first five minutes, followed by 25% within ten minutes, and 4% between 15 and 20 minutes (Fig. S3). These findings indicate that most of the sample was composed by PE, which melts within five minutes, with a smaller portion of PP, requiring more than five minutes to melt, as shown in the previous section. This interpretation is consistent with the FTIR results (Fig. S2d).

3.3. *Preliminary field trial as part of the citizen science protocol*

During the pre-field trial in May 2025, a total of 120 particles collected from Guidel Plage beach were analysed by volunteers. The volunteers analysed samples containing known quantities of MPs, identifying 122 particles as MPs across all samples. Following the melting protocol, 75 particles melted and 47 remained unmelted. Based on the initial number of MPs, the false negative rate was 37.5%, corresponding to a recovery rate of 62.5%. However, the visual counts reported by volunteers were consistently higher than the actual number of particles initially present (Fig. 4). This indicate that loss of particles during sieving was more than compensated by the misidentification of non-plastic debris during visual sorting (false positive). Consequently, the results demonstrate a tendency to overestimate MPs abundance.

The highest misidentifications occurred in samples GP25-3 and GP25-6 (Fig. 4), which contained the greatest number of MPs ($n = 50$). However, the interaction between false negative rate and the initial particle counts in samples (i.e., MPs mixed with natural material) was not statistically significant (all $p > 0.1$), likely due to the small sample size ($n = 4$). Regarding particle size, a higher mean error rate was noted in the 1-2 mm fraction, at 0.515 ± 0.360, compared to 0.215 ± 0.255 in the 2-5 mm fraction, but no significant difference was observed ($t = 1.3619$, $n = 4$, $p = 0.227$).

Regarding melting times, the majority of the particles identified as MPs melted within five minutes (59%), followed by 23% within 10 minutes, 14% within 15 minutes and 4% within 20 minutes (Fig. S4). The volunteers' results reflect the overall pattern of polymer composition. PE remained the dominant polymer, with slight underestimation compared to the initial count of 84%, while PP accounted for 41%, with a slight overestimation compared to the initial count of 36%.

3.4. *Final field trial with expedition MED 2025*

MPs were found in all samples collected at the surface of the Mediterranean Sea in 2025 ($n = 19$), with plastic's abundance ranging from 1 to 594 particles. A total of 3,648 particles identified as potential plastics were collected of which 227 belonged to the > 5 mm size class (meso and macro plastics), and 3,421 particles were potential MPs. Among MPs, particles within the size range 1-2.5 mm were the most abundant (65%), followed by those in the 2.5-5 mm range (27%) (Fig. S5a). The predominant shape category across all samples was fragment (60.5%), followed by film (29%), filament (9%), foam (1%) and pellet (0.5%) (Fig. S5b). Regarding the colour, transparent was the most common colour (37%), followed by white (20%). Black, multicolour, yellow, green, blue and orange accounted for less than 10% each and brown and pink less than 5% (Fig. S5c).

From the 3,421 particles tested, 3,119 melted during the heating verification step, leaving only 302 particles unmelted, corresponding to an error rate of 8.8%. However, 49.1% of these remaining particles were visually identified as microplastics (i.e. transparent film and colored filament) that had failed to melt due to insufficient contact with the

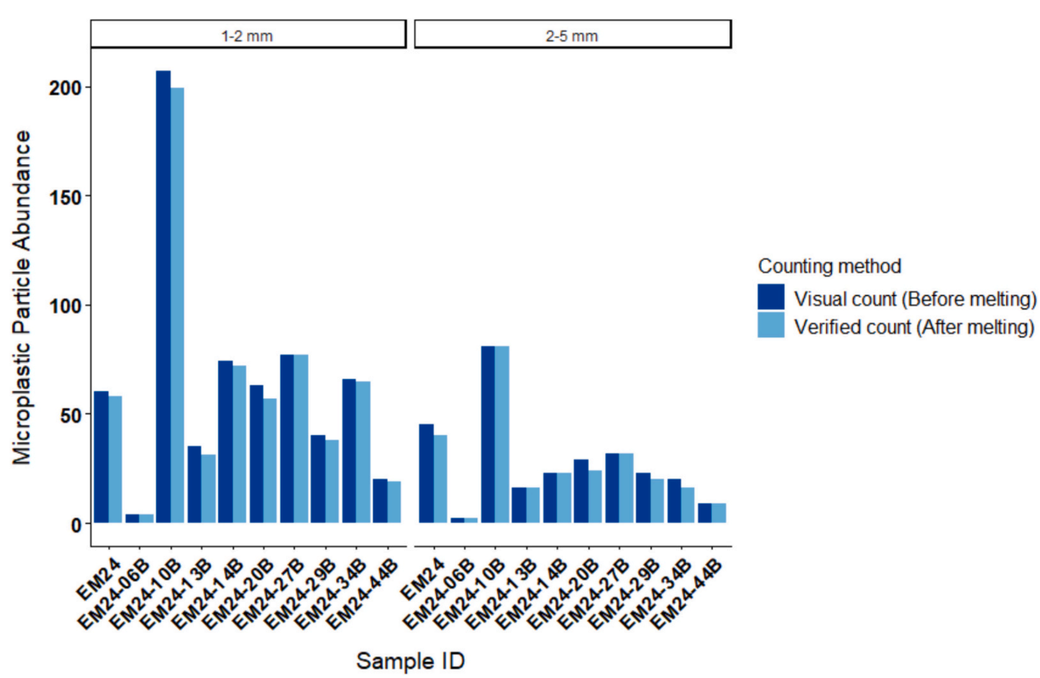

Fig. 3. The visual abundance (before melting) of particles identified as microplastics and their confirmed abundance (after melting) for the 2024 Expedition MED campaign. Differences between visually identified and melting-confirmed counts were analysed using a Wilcoxon test ($p > 0.05$).

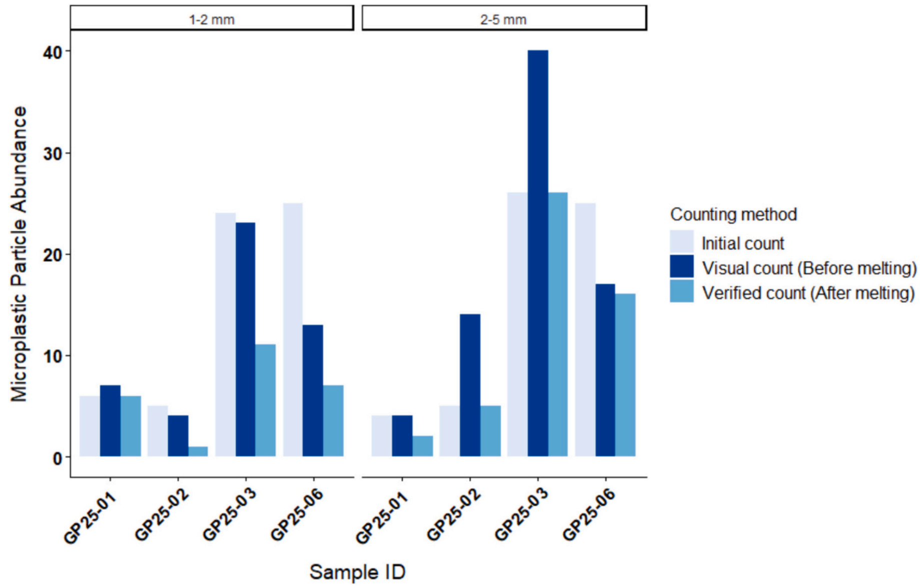

Fig. 4. Initial count, visually identified and verified abundance of microplastic particles in prepared samples during the preliminary field trial with volunteers for Guidel Plage beach samples.

heated ceramic plate. Some samples (EM25-13, EM25-41 and EM25-21), which had the highest concentrations of MPs and were the smallest in size, showed the greatest differences between the particles initially identified as MPs and those confirmed as MPs after the melting test (Fig. 5). Most of the particles melted within the first ten minutes (85%) (Fig. S6). However, no significant differences were found between the rate of false positives compared to the size class ($W = 187.5$, $p = 0.62$) and compared to the initial abundance of particles ($Z = 0.7$, $p = 0.4$).

4. Discussion

4.1. A new microplastic detection tool to help citizen science

Visual identification of MPs is subject to false positives, particularly in samples with high particle abundance, as it is a time-consuming step, therefore prone to human error (Song et al., 2015). Similar observations were made in our study, insofar as the rate of misidentification rate under a binocular magnifying glass tended to be more frequent in samples containing more than 400 particles per sample, as well as with particles within the 1.0 – 2.5 mm size range. Furthermore, the elevated organic matter content observed during spring and summer months, particularly plankton (Collignon et al., 2014; Collignon et al., 2012), made the sorting process more difficult by increasing the number of non-plastic particles in the samples. In particular, transparent fragments of *Posidonia oceanica,* which are highly prevalent in the Mediterranean Sea (Alomar et al., 2024; Stipcich et al., 2024) were frequently misidentified by volunteers as transparent film-like MPs. Other natural materials such as salt crystals, were also occasionally mistaken for plastics by the volunteers due to their irregular shapes and white colour. Similar confounding materials, like coal and quartz, have been widely reported to cause overestimation of MPs concentrations, ranging from 20% up to 70%, in the absence of verification analysis (Eriksen et al., 2014;

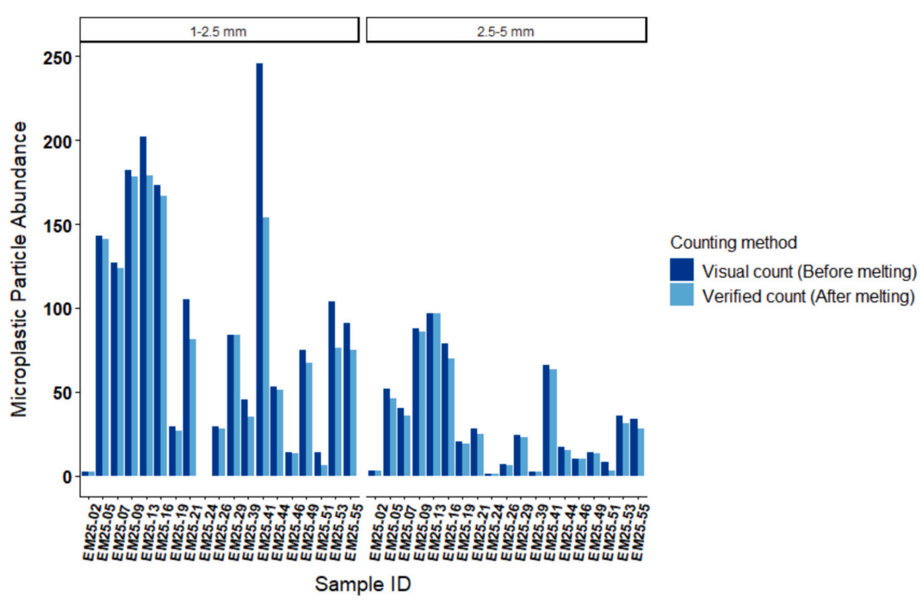

Fig. 5. The visual abundance (before melting) of particles identified as microplastics by the volunteers and the confirmation abundance (after the melting) of the 2025 Expedition MED campaign. Difference between visually identified and melting-confirmed counts were analysed using a Wilcoxon test ($p > 0.05$).

Hidalgo-Ruz et al., 2012; Lenz et al., 2015; Löder et al., 2015). These factors confirmed the need for a simple tool to help volunteers confirm the nature of the particles collected in a simple and inexpensive manner. These observations led to the development of a reliable tool for MPs detection made on this study.

The development of the ceramic plate was prompted by the need for a support tool that could facilitate individual particle observation, withstand high temperatures, and remain inexpensive, accessible, and reproducible. This addresses the limitations of both commonly used materials in MPs research: Petri dishes, which lack particle separation, and microplates, which are made of plastic (Kedzierski et al., 2019). For this study, more than 80 ceramic plates were produced and tested, demonstrating stable heat, and reaching a temperature close to 200 °C. Despite some minor limitations, the ceramic plates offer several key advantages from a technical perspective. The new support tool allows for clear particle organisation, can withstand repeated high-temperature exposure up to 200 °C without deformation, and can be heated up to 900 °C (Geng and Sun, 2018), allowing the study of polymers with higher melting points. The design is also fully customizable; the cavity size and plate thickness can be adjusted during fabrication to suit specific experimental requirements. Moreover, it is made of a low-cost and accessible material (around 0.04 euros in material costs per ceramic plate). Importantly, volunteers from environmental associations, schools or community groups can actively participate in fabricating these plates. Therefore, the ceramic plate support represents a reliable, durable and adaptable alternative tool for a citizen science project on MPs identification.

Compared to other thermal verification methods such as the hot needle, our approach provides significant advantages. First, the protocol offers a moderate analysis time and is particularly suited for highly polluted marine environments, such as the Mediterranean Sea, where more than 400 particles may be present in a single sample. Furthermore, whereas the hot needle test is limited to detecting MPs one by one, which takes a long time for large sets of particles, our approach allows us to work directly on 105 particles by ceramic plate. This applies well to citizen science projects, where volunteers typically analyse one to two manta samples with dozens or hundreds of plastics per day. However, limitation of the field campaigns (Expedition MED 2024 and 2025) is that the false negative could not be calculated. Unlike pre-field trial, real marine samples contain an unknown and high amount of non-plastic debris, making them difficult to analyse on board. In the future, a subset of these unselected particles could be collected and analysed to quantify the false negative rate. Others limitations of the protocol identified at this stage, it is possible to mention the variations in melting time that were observed. These phenomena could be explained by fabrication irregularities in the ceramic plate, differences in polymer composition (e.g., presence of impurities or additives) (Majewsky et al., 2016; Rodríguez Chialanza et al., 2018; Sorolla-Rosario et al., 2022), and the particle form. This last aspect seems to be the major confounding factor. In fact, due to their shape, particles such as filament have sometimes a very small contact surface with the ceramic substrate, resulting in a potential delayed or incomplete melting. To mitigate this issue, placement techniques, such as flattening filament to maximize the contact area, could improve the melting. Additionally, a lid could be implemented in future designs. Nevertheless, despite this variability, the protocol remains reliable. Therefore, the incorporation of a rapid melting verification step successfully reduced false positives by bringing the error rate down to just 8.8%.

Our developed methods were specially designed for the major polymers encountered at the water surface (Cincinelli et al., 2019), notably PE and PP. It enables plastic particles detection, within 20 minutes at a temperature of 200 °C. In our experiment, more than 60% of particles typically melted within the first five minutes, with an additional fraction melting by ten minutes, providing a rapid estimate of the abundance of PE and PP, respectively. While targeting PE and PP aligns with the dominant composition of Mediterranean surface waters, it represents a limitation when comparing datasets with laboratory studies that analyse a broader polymer diversity. However, the flexibility of this thermal verification allows for future adaptations. For example, introducing an intermediate observation point at approximately two minutes could enable finer classification by distinguishing low-density polyethylene (LDPE; 109–110 °C) and high-density polyethylene (HDPE; 125–139 °C) (Lee et al., 2024; Sorolla-Rosario et al., 2022). Furthermore, the protocol can be expanded to include polymers with higher melting temperatures, such as PA (220.56 ± 0.49 °C, Lee et al., 2024), the heating step can be performed at elevated temperature, as the heat plate used allows setting up to 400 °C (i.e., temperature used to clean our ceramic plates) and beyond.

Our approach ensures the reliability of work based on participatory science. It demonstrates that citizen science initiatives, when combined with verification steps based on rigorous methodologies developed by scientists, can generate robust and trustworthy data. Consequently, datasets collected in the field can be directly compared with those produced by laboratory research, reinforcing the scientific value of citizen science in monitoring sea-surface MPs.

4.2. *Feedback on working with volunteers*

4.2.1. *Participation and feasibility*

The protocol was implemented across four different environmental associations and tested by 39 volunteers aged from under 18 to over 65, with diverse socio-demographic backgrounds (Table S3). Some participants had previous experience in citizen science projects, while others did not. Nevertheless, all volunteers were able to understand and successfully follow the protocol instructions, demonstrating that it does not require pre-existing skills and is accessible to a wide range of participants.

Some challenges were observed during two more complex steps: categorising MPs, which was unfamiliar to many participants (50% reported no prior experience) and determining when a particle had truly melted, as particles display different behaviours during heating, such as shrinking, changing shape or surface area without fully liquefying. Differences in performance between the pre-field trial, where volunteers had only one single afternoon of training, and the final trial, which underwent a full week of practice, highlight the critical role of training for reducing MP misidentification rates in these more complex tasks. Similar findings were reported in the study by van der Velde et al. (2017), where it was observed that multi-day training in marine litter collection produces better performance than single-day sessions.

Participants' difficulties and performance emphasise the importance of structured, face-to-face training with demonstrations, support, and practical exercises in the field, which are essential for minimising errors and ensuring high data quality (Kawabe et al., 2022). Besides training, simple validation steps, such as having an experienced participant or pairing participants to cross-check observations, can further improve data robustness and reliability (Balázs et al., 2021).

Importantly, volunteers found the protocol easy to follow and enjoyed the activity itself. Many were motivated by the opportunity to learn new skills, contribute to a scientific project, and engage in environmental protection. By keeping field activities fun, engaging, and manageable, citizen science participants are more likely to stay committed, which enables repeated and large-scale monitoring programs (van Noordwijk et al., 2021). Overall, these findings suggest that the protocol is feasible, capable of producing robust results, and also provides a new positive and motivating experience for participants.

4.2.2. *Limitations*

Some temperature variations were observed while using the ceramic plates, especially between the central and the peripheral positions, due to an uneven contact with the heating source. Improvements in the production should be made to minimise the fabrication irregularities affecting plate thickness and flatness. Precisely, improvement during the drying process will be crucial to enhance the quality of the ceramic plate, as high levels of water are eliminated, leading to a loss of mass and contraction of the material (Zaccaron et al., 2024). Potentially, placing the ceramic plate on a cooling wire rack and adding a lightweight object to the plate could improve the flattening, allowing the diffusion of water and evaporation on the surface (Zaccaron et al., 2021).

Engaging people who may have no prior exposure to scientific practices is highly valuable, but it also comes with challenges. Many participants can underestimate the amount of time, attention and energy required to complete complex tasks. Volunteer fatigue was one of the key limitations encountered when working with citizen science. Activities such as hauling the manta trawl or identifying small particles under challenging climatic conditions require effort and concentration, and fatigue can lead to reduced attention and, very probably, increased error rates. Demographic factors also play a role, as older volunteers may experience greater difficulty with tasks requiring visual acuity or physical strength compared to younger participants. To help overcome such limitations, alternatives such as using a large, fixed magnifier, rather than a stereomicroscope, which can induce seasickness in some participants, can make visual identification less physically demanding. To maintain high data quality and reduce the risk of volunteer dropout, complex activities are advised to be broken down into activities that take less time and effort (Rambonnet et al., 2019). Specially, volunteer should rotate their roles and switch activity every 30 minutes to prevent fatigue from performing the same task for extended periods.

Another key limitation was the environmental conditions. In fact, it is well known that during the collection of floating MPs at sea, parameters such as the wind speed, wave height and the presence of organic material can significantly affect sampling with a manta trawl (Setälä et al., 2022). Boat speeds exceeding 3 knots can destabilise the manta, while high wave heights can cause the flowmeter to intermittently exit the surface water, resulting in inaccurate estimations of the total volume filtered (Pasquier et al., 2022). These challenges were particularly present during the 2025 Expedition MED campaign in the Mediterranean Sea, where we encountered sea states of up to 1.0 m and where it is known that waves can reach heights of up to 1.25 m (Barbariol et al., 2021). When analysing particles that may be MP, melting verification must be carried out outside the boat to avoid breathing the toxic smoke that might be produced when the particles melt. Moreover, it is safer to work with the heat plate in calm conditions. Therefore, careful handling and manipulation in outdoor conditions are essential, especially under strong wind conditions, to prevent particles loss due to their light weight (Liu et al., 2025). Alternatively, melting verification can be performed inside a transparent box to minimise particle loss.

Consequently, calm meteorological conditions will ensure both the accuracy of the sample collection as well as the analysis by the volunteer by reducing their physical demand.

4.3. Results of missions in the Mediterranean Sea

4.3.1. Enhancing the potential of citizen science campaigns

One of the key lessons learned from this new protocol is that this verification step, whether on land or at sea, enables the production of rapid finalised datasets within just a few months. In contrast, other citizen science studies (De Haan et al., 2022; Jones et al., 2025; Nel et al., 2020; Pasolini et al., 2023; Setälä et al., 2022; Walther et al., 2024), which rely on laboratory analyses by researchers, shows longer delay between sampling and data publication (Fig. 6). In our case, the data collected and analysed in the field during the 2025 Expedition MED campaign in the Mediterranean Sea were processed within only two months, one month dedicated to sampling and data acquisition in the field and one month to analyse the results.

This reliance on laboratory expert analysis, rather than direct field analysis by trained volunteers, can prolong project timelines due to the need for sample transport and storage, a process that increases the risk of particle loss or sample degradation (Isobe et al., 2019). When combined with the time-intensive nature of MPs' data analysis and management, this often results in delays of several years, particularly in long-term monitoring projects (Danopoulos et al., 2023). Moreover, achieving high spatial resolution requires intensive sampling across multiple sites. When combined with laboratory analysis, these time constraints can limit both the number of samples that can be processed and the geographical extent that can be monitored (Stock et al., 2020).

This delay also complicates the interpretation of the temporal trends

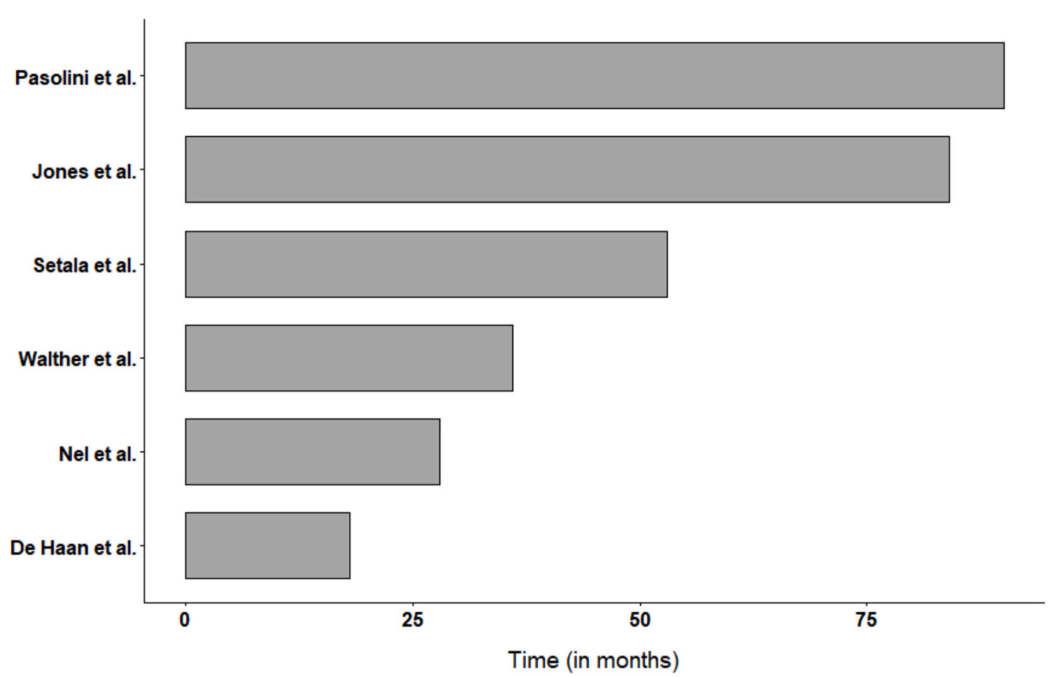

Fig. 6. Delay between the data collection and the publication across selected citizen science studies (Nel et al., 2020 (sampling : June 2018); Setälä et al., 2022 (sampling : May 2018); De Haan et al., 2022 (sampling : October 2020); Pasolini et al., 2023 (sampling: 2016); Walther et al., 2024 (sampling : September 2021); Jones et al., 2025 (sampling March 2018)). Bars indicate the time elapsed (in months) between data collection and its publication.

of the sea surface MPs concentration. Consequently, reported concentration usually describes past conditions rather than the state of the environment at the time of the publication. By comparison, the developed protocol allows data collected in 2025 to be presented within the same year, providing an up-to-date representation of the current state of MP concentrations. This is particularly critical as MP distribution varies over time due to the impact of hydrodynamic conditions and seasonal circulation influencing their transportation(Kukulka et al., 2012; Pedrotti et al., 2022; Zayen et al., 2020), as well as their abundance impacted by riverine inputs, potential episodic events such as storms and floods and seasonal tourism (Cincinelli et al., 2019; Philip et al., 2025).

4.3.2. Citizen scientist monitoring floating microplastics on the surface of the Tyrrhenian Sea

Citizen scientists provided effective monitoring of the abundance and distribution of floating MPs across a wide geographic area during the 2025 Mediterranean expedition. Analysis of 19 samples reported information about the spatial variability within the Tyrrhenian Sea. The observed distribution of MPs was highly heterogeneous, with clear differences between stations. For example, high abundances were recorded along the Corsican coast, while lower concentrations were observed in the south eastern waters of Sardinia (Fig. 7).

The average concentration of floating MPs, within the size range 1 – 5 mm, recorded during the 2025 expedition MED was 0.9 ± 1.01 items/m^3. This value is higher than those reported in previous studies from the same region (Baini et al., 2018; Fossi et al., 2016; Panti et al., 2015; Pedrotti et al., 2022; Pittura et al., 2022). An important factor to consider is the difference in size classes reported across studies. Most monitoring research measured MPs within broader size ranges, typically from just below 5 mm down to the lower detection limit imposed by the mesh size of the net (0.2 mm) (Table 2). Pittura et al. (2022) extended their analysis to particles as small as 0.01 mm, which was possible through FTIR-based detection. Conversely, Pedrotti et al. (2022) reported higher concentrations, but these included a much larger size spectrum, from particles above 20 mm down to 0.3 mm. In our cases, all particles smaller than 1 mm were excluded to simplify the workflow of the volunteers. Although particles in the 0.3 – 1 mm range could be analysed directly in the field, as the particles are still visible using a stereomicroscope or a magnifier, this would require substantially more time and effort, and visual characterisation alone remains limited without the support of advanced laboratory techniques.

Such a large range in size class definitions complicates direct comparisons between studies. To harmonise results and allow for more

Table 2
The average concentration of floating microplastics (items/m^3 ± SD) in the Tyrrhenian Sea from 2024 and 2025 campaigns of Expedition MED, with bibliographic data adapted from Fossi et al. (2016), Panti et al. (2015), Baini et al. (2018), Pittura et al. (2022), Pedrotti et al. (2022).

Reference	Year	Location	Sample (n)	Size range (mm)	Items/m^3 ± SD
Present study	2025	Tyrrhenian	19	1 – 5	0.9 ± 1.01[a]
	2024		10	1 – 5	0.3 ± 0.29[a]
Pittura et al.	2019	Tyrrhenian	-	0.01 – 5	0.195
	2017	Tyrrhenian	-	0.01 – 5	0.194
Pedrotti et al.	2014	Tyrrhenian	33	0. 3 – > 20	2.93 ± 9.11
Fossi et al.	2013	NW Sardinian	36	0.2 – 5	0.16 ± 0.31
Baini et al.	2013	Tyrrhenian	33	0.5 – 5	0.26 ± 0.33
Panti et al.	2013	NW	13	0.2 – 5	0.24 ± 0.43
	2012	Sardinian	14	0.2 – 5	0.10 ± 0.12

[a] (2025 median: 0.54 items/m^3, IQR = 0.2-1.1; 2024 median: 0.3 items/m^3, IQR = 0.15-0.3)

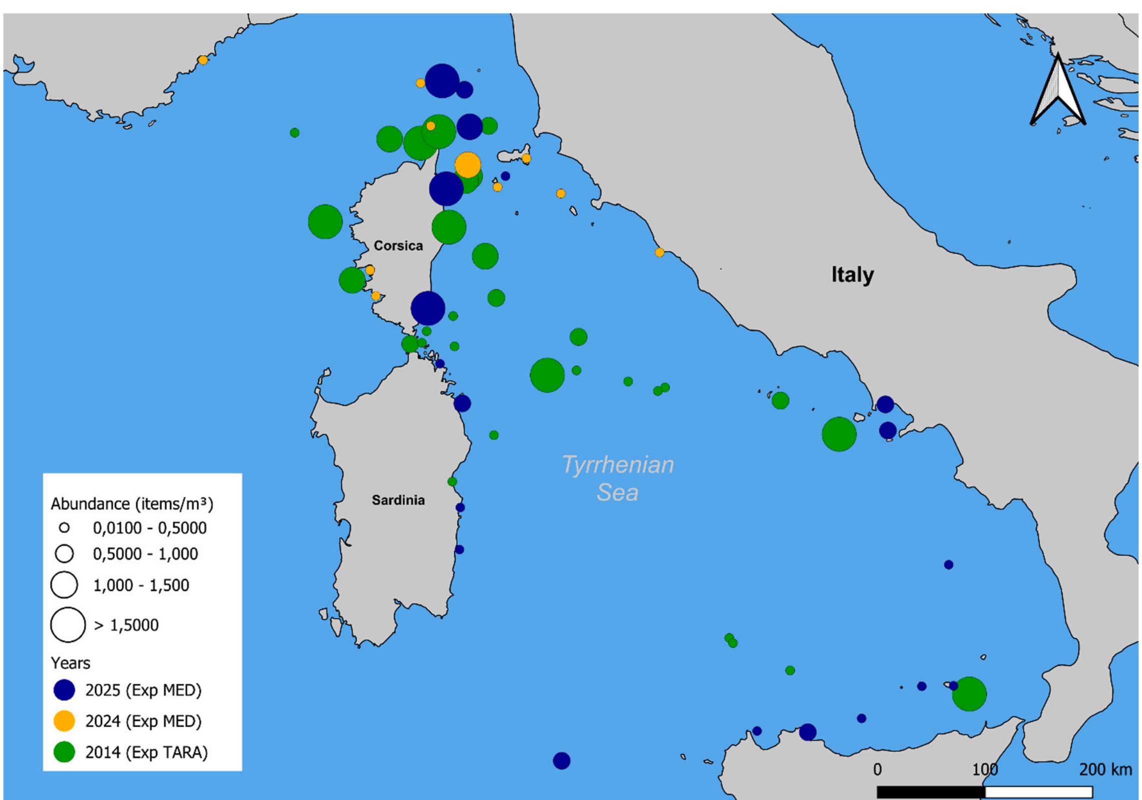

Fig. 7. Spatial distribution of floating microplastics concentration (items/m^3) in the Mediterranean Sea, based on data from three expeditions: Expedition MED 2025 (blue), Expedition MED 2024 (yellow) and the TARA expedition 2014 (green) adapted by Pedrotti et al. (2022). Circle size is proportional to the measured concentration, ranging from 0.01 to > 1.5 items/m^3.

accurate cross-study comparisons, mathematical scaling approaches such as the Koelmans' equation (Koelmans et al., 2020; Kooi et al., 2021) can be applied to normalise concentrations across different size ranges.

Across studies, a consistent feature that enables comparison is the dominance of fragment particles, which remain the most common shape of MPs reported in the Mediterranean Sea (Baini et al., 2018; Fossi et al., 2016; Panti et al., 2015; Pedrotti et al., 2022; Pittura et al., 2022). In addition, transparent and white were the most frequently reported colours in the 2024 and 2025 Expedition MED campaigns, one variable not described in previous cited studies but recognised as globally dominant in the marine environment (Martí et al., 2020).

Distinct hotspots of MPs concentrations were identified along the north-eastern coast of Corsica, overlapping with the area influenced by the '*Capraia Gyre*', a current system previously described as a potential accumulation zone of marine debris (Fossi et al., 2017). Similarly, the Corsica Channel has been identified as a major accumulation area where circulation patterns enhance debris retention (Baudena et al., 2022; Caldwell et al., 2020; Pedrotti et al., 2022; Suaria et al., 2016). These hydrodynamic features likely account for the elevated particle abundance recorded during the 2025 expedition MED, which closely aligns with the high concentration observed during the 2014 Tara expedition undertaken in the same region (Pedrotti et al., Fig. 7). The consistency of these results across two independent campaigns highlights the persistence of this MPs' hotspot over time. However, contrasting results were obtained during the 2024 expedition, with a nearby station showing much lower concentrations. These differences can be explained by variable oceanographic conditions from year to year, such as wind, waves and currents. To better understand these temporal fluctuations, it is necessary to conduct repeated sampling at the same stations over time.

High concentrations of MPs were also collected along the south-eastern coast of Corsica, which is likely influenced and transported by the cyclonic gyre in the northern Tyrrhenian Sea, as described by Fossi et al. (2017). This gyre pushes floating debris toward the Strait of Corsica, an area previously reported in past years as a hotspot for plastic accumulation (Pedrotti et al., 2022).

Beyond oceanographic drivers, anthropogenic activities must be also considered when looking at the distribution of MPs. Intense tourism (i. e., 1.3 billion worldwide arrivals), which is a major economic driver in the region and is valued at 3.4 billion USD, also contributes to plastic pollution (World Tourism Organization, 2024). Up to 80% of marine debris on Mediterranean islands and beaches has been attributed to tourism-related activities (Grelaud and Ziveri, 2020; Mejjad et al., 2022). Our results also revealed MP concentration near large coastal cities, including Fiumicino, Bastia, Bonifacio, Palermo and Olbia (Fig. 7), where busy harbours and intense maritime traffic contribute significantly to local pollution sources (Liubartseva et al., 2018).

5. Conclusion

This study demonstrated the feasibility and scientific value of a simplified protocol for monitoring floating MPs through citizen science. By integrating a rapid heating verification step and the development of reproducible ceramic plates, the protocol enabled efficient polymer screening in the field, and reduced false positives, ensuring that data generated by volunteers are directly comparable to those produced through laboratory analyses. The approach proved particularly suited for the most abundant surface polymers found in the global ocean, PE and PP, while maintaining accessibility and low cost, thus facilitating large scale and long-term monitoring.

Field application during the 2025 expedition MED highlighted the capacity of citizen scientists to collect meaningful data across a broad geographic scale. Results revealed highly heterogeneous distributions of MPs, with consistent hotspots identified in the Corsica Channel and north-eastern Corsica, aligning with previous scientific campaigns such as the TARA expedition. This reinforces the reliability of citizen-generated datasets for advancing our understanding of spatial variability in MP pollution.

Nevertheless, limitations were observed, notably volunteer fatigue, environmental constraints during sampling, and the inability to identify polymer types beyond PE and PP. These challenges underscore the importance of structured training, task rotation, scheduling expeditions during the most favourable environmental conditions and complementary laboratory verification when higher analytical precision is required.

Overall, this study shows that citizen science can complement traditional MPs research, notably the delays linked to laboratory analysis and data publication. While this low-cost method cannot replace advanced analytical instruments; instead; it provides a rapid field-screening alternative. By providing near-real-time datasets, this protocol enhances the capacity to track temporal trends and strengthens the role of citizen science in environmental monitoring.

CRediT authorship contribution statement

Elora Briola: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Solene Cleraux:** Writing – review & editing, Resources. **Bruno Dumontet:** Resources, Project administration, Funding acquisition. **Ana Luzia Lacerda:** Writing – review & editing, Resources, Project administration, Investigation. **Mikaël Kedzierski:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2026.120084.

Data availability

Data will be made available on request.

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