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Validating citizen science for community-driven microplastic monitoring and marine protection in Northeast Iceland's Hope Spot

Belén G. Ovide [a,*], Eleonora Barbaccia [b], Claudia Lorenz [c], Charla J. Basran [a], Erica Cirino [d], Kristian Syberg [c], Marianne H. Rasmussen [a]

[a] University of Iceland's Húsavík Research Center, Hafnarstétt 3, 640 Húsavík, Iceland
[b] Politecnico di Milano DICA Civil and Environmental Engineering Department, Piazza Leonardo da Vinci, 32, 20133 Milano, MI, Italy
[c] Department of Science and Environment, Roskilde University, Roskilde, Denmark
[d] Plastic Pollution Coalition, 4401A Connecticut Avenue NW #143, Washington, DC 20008, USA

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ABSTRACT

Governments are increasingly monitoring meso- and microplastic (M/MP) pollution in surface waters to develop cost-effective solutions. While citizen science is widely used in programs like the EU's Marine Litter Watch and NOAA's sampling in the U.S., these efforts primarily focus on macro litter, leaving gaps in M/MP data, especially in under-sampled regions like Icelandic waters. This study addresses this gap through a citizen science initiative (2019–2023) that monitored M/MP pollution in the "Northeast Iceland Hope Spot." Fifty-eight trawl samples were collected from whale-watching and expedition vessels using a low-tech aquatic debris instrument (LADI) or a high-speed AVANI trawl. M/MP were present in 86 % of samples, with an average density of 0.02 ± 0.03 particles/m^3. Concentrations varied significantly between sites ($p = 0.005$), peaking in Grímsey (0.070 ± 0.03 particles/m^3), followed by Eyjafjörður (0.006 ± 0.04 particles/m^3) and Skjálfandi Bay (0.004 ± 0.03 particles/m^3). Mesoplastics comprised 44 % and microplastics 56 %, primarily polyethylene (47 %) and polypropylene (39 %)—common materials in fishing gear and household plastics. These findings suggest that local currents and fishing activities influence M/MP distribution. Comparison with previous studies validates the use of the presented citizen science methods for tracking floating M/MP in coastal waters and highlights their value in shaping marine conservation policies, particularly in vulnerable subarctic ecosystems.

1. Introduction

Monitoring plastic pollution is critical to assess the health of marine ecosystems and gather key information to develop marine conservation plans (Hoyt, 2012). The Arctic plays a vital role in regulating the global climate and supporting life on Earth and therefore, it must be preserved. Despite their ecological significance, these waters–often mistakenly considered remote or "pristine"–are not exempt from the issue of plastic pollution (Lloyd-Jones et al., 2023). Alarmingly, microplastics have been reported everywhere across Earth's ecological compartments (Singh, 2022) such as soil, sediments, glaciers, fresh water, air, animals, human bodies, and sea surface water (Wang et al., 2019; Ambrosini et al., 2019; Fogašová et al., 2022; Susanti et al., 2020; Kannan and Vimalkumar, 2021; Eriksen et al., 2014a); including Arctic waters (Bergmann et al., 2022) (e.g., in the Greenland Sea (Liboiron et al., 2021), the Arctic Central Basin (Kanhai et al., 2018), and in Svalbard fjords (Lusher et al., 2015a)).

The presence of plastic particles in ecosystems and organisms is a growing environmental and health concern (Prata et al., 2021). Due to the polymer chemistry and persistence of conventional plastics, all plastic items and coatings do not degrade benignly over time but instead shed plastic particles (Andrady, 2017): mesoplastic (5 mm–10 mm), microplastic (1 μm–5 mm), and nanoplastic (<1 μm) (Kershaw and Rochman, 2015). Increasing evidence suggests that meso- and microplastics (M/MP) negatively impact wildlife and humans and disrupt biogeochemical ocean processes and the climate (Galloway et al., 2017). The impact of M/MP can cause direct disruption of organs, impairment of reproductive functions, and severe physiological changes in the metabolism (Anbumani and Kakkar, 2018). This is an even greater concern in marine ecosystems and other aquatic environments, where

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* Corresponding author.

E-mail addresses: bgo4@hi.is (B.G. Ovide), eleonora.barbaccia@polimi.it (E. Barbaccia), lorenz@ruc.dk (C. Lorenz), cjbasran@hi.is (C.J. Basran), erica.cirino@plasticpollutioncoalition.org (E. Cirino), ksyberg@ruc.dk (K. Syberg), mhr@hi.is (M.H. Rasmussen).

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the shedding of plastic particles is often accelerated by a combination of mechanical stressors such as sunlight and wave action (Fernández-González et al., 2021).

Oceanic islands such as Iceland are highly vulnerable to M/MP pollution due to the complex nature of their coastal ecosystems and the interactions between biotic and abiotic components (Monteiro et al., 2018). The unique current systems and tidal patterns in Northeast Iceland are essential for ecosystem functioning, facilitating the distribution of sediment, plankton, and nutrients. These ecosystems provide critical feeding grounds for resident and migratory whale species, including humpback whales (*Megaptera novaeangliae*) and endangered blue whales (*Balaenoptera musculus*), as well as important nesting habitat for seabirds and breeding grounds for seals (CBD, 2001). However, these ocean dynamics also act as pathways for microplastic transport, making this productive yet fragile area vulnerable to becoming a hotspot for plastic pollution accumulation. To date, M/MP in Iceland have been reported in marine sediments (Loughlin et al., 2021), glacier cores (Stefánsson et al., 2021), drinking water (ReSource, 2021), fulmar stomachs (Kühn and van Franeker, 2012) and possibly capelin (Brawn et al., 2023), as well as on the sea surface (Ovide et al., 2022). Historically, there has been a lack of research on coastal M/MP in Iceland and on coastal marine research in general. However, a growing body of research has identified fishing gear as one of the most prevalent types of plastic debris on remote Icelandic beaches (Kienitz, 2013; Hafrannsóknastofnun, 2019; O'Rourke, 2020), suggesting that nets and ropes may be a major contributor to plastic pollution in the Icelandic marine and coastal environments (Ocean Missions, 2024).

In June 2023, Iceland launched, the “Northeast Iceland Hope Spot,” as a step towards establishing a marine protected area. Mission Blue Hope Spots are designated marine areas that are critical to global ocean health due to their ecological importance and biodiversity (Mission Blue, n.d.). These non-legally binding designations are intended to inspire communities and governments to protect marine areas in line with the United Nations Convention on Biological Diversity's goal of protecting 30 % of the planet by 2030 (UN, 2022). Coastal communities such as Húsavík and Akureyri, known for research and whale tourism, contribute to the importance of the area (Hoyt, 2001; O'Connor et al., 2009). In 2023, Iceland received over 2.2 million international tourists, a fourfold increase since 2010 (excluding the years 2020 and 2021, which were affected by the COVID-19 pandemic) (Iceland Tourism Statistics, 2024). Currently, <2 % of Iceland's marine areas are fully protected (Government of Iceland, 2023). The lack of a comprehensive legal framework underscores the urgent need for robust science to support marine protection against potential impacts from anthropogenic activities, such as plastic pollution, mass tourism, inadequate whale-watching regulations, and the development of poorly managed ocean-related industries, including aquaculture (SVÍVS, personal communication, 2024).

Current M/MP monitoring efforts in the Arctic have been fragmented, with insufficient monitoring of ecosystem conditions, resulting in significant knowledge gaps. Therefore, the Arctic Council emphasizes the need for ecosystem monitoring and cooperation at the pan-Arctic level. Since 2021, an Arctic monitoring program has established best practices for tracking microplastic pollution considering multiple environmental matrices, using different methods, and across different Arctic compartments (e.g., sediments, ice, subsurface, and sea surface). These practices will be based on global monitoring programs, tailored to the unique and evolving conditions of the Arctic environment (AMAP, 2021). M/MP data collection in the Arctic and/or sub-Arctic regions, such as Iceland, is constrained by extreme climatic conditions and seasonal variability, resulting in limited sample sizes. In addition, logistical challenges and high costs associated with working in semi-remote environments further hinder research efforts (Mallory et al., 2018), which often complicates comparisons with data from other marine debris networks outside of the Arctic (e.g., NOAA, 2011; OSPAR, 2015). Given these challenges, ecosystem-based approaches such as community-based citizen science initiatives, can amplify data collection efforts and provide complementary information to better understand the scale of the problem and its potential impacts in areas of biological importance (Butler et al., 2023; Provencher et al., 2023).

Citizen science is widely recognized as a valuable tool for investigating plastic pollution and raising public awareness. However, few projects have engaged citizen scientists in the systematic collection of M/MP pollution data, likely due to the technical complexity of sampling methods and concerns about potential sources of contamination such as plastic-based clothing, laboratory equipment, sampling tools, and other sources (Setälä et al., 2022). However, when rigorously designed and monitored, citizen science-based sampling projects have been shown to provide reliable data that can effectively complement ongoing conservation efforts. For example, a successful citizen science pilot - study in 2022 revealed the heterogeneous distribution of M/MP in six nearshore stations in northern Iceland (Ovide et al., 2022) using harmonized protocols from whale-watching boats and expedition vessels. Standardized protocols for microplastic monitoring include surface sampling in marine environments using trawls. This approach combines an accessible research tool with a pragmatic method (Karlsson et al., 2020) and it is particularly suitable for citizen science, which, when well-planned and supervised by experts, can provide high-quality samples of microplastics from surface waters (Setälä et al., 2022; Gewert et al., 2017). In a recent study, Mallory et al. (2021) addressed how incorporating citizen science programs aboard Arctic cruises may be beneficial for identifying, mapping, and monitoring the health of areas of particular conservation importance (Alves et al., 2018). This inclusive approach fosters greater interest in marine life and its conservation while addressing gaps in scientific research (SINAY, 2023). In addition to the obvious benefits of enhancing marine research, citizen science raises awareness of marine conservation and fosters public engagement, adding value to the tourism experience by allowing participants to actively contribute, creating a more meaningful and immersive experience.

The present study evaluated M/MP pollution in localized coastal marine environments within the “Northeast Iceland Hope Spot” and demonstrates the power of citizen science as a key resource. The primary objectives of this study were to address the following research questions: (1) what is the baseline assessment of the occurrence of M/MP in the Northeast Iceland Hope Spot? (2) how can citizen science approaches reliably help monitor M/MP pollution and contribute to marine conservation efforts to advance the protection of biologically important areas? and (3) what knowledge gaps remain to be addressed? Therefore, we 1) assessed spatiotemporal distributions across sampling sites and identified the types of M/MP, 2) evaluated and validated the effectiveness of the citizen science approach by scrutinizing the methods and comparing our results with existing research on M/MP pollution in the Arctic, and 3) discussed what remaining knowledge gaps can be addressed through a similar citizen science approach.

2. Methods

2.1. Study area

The Northeast Iceland Hope Spot (Fig. 1) covers 1067 square nautical miles (NM) (1976 km^2), with 176 NM (326 km) of coastline, and is located in the Northeast Iceland region. The geographical boundaries of the Northeast Hope Spot are: 18° 03′ 50.74″ W; 66° 45′ 52.23″ N (Northerly boundary - coinciding with the 12-mile territorial sea boundary), 18° 04′ 23.23″ W; 65° 41′ 38.57″ N (Southerly boundary), 18° 37′ 54.95″ W; 66° 10′ 04.74″ N (Westerly boundary) and 17° 09′ 51.64″ W 66° 11′ 58.06″ N (Easterly boundary).

The Northeast Iceland Hope Spot includes three biologically critical regions: Skjálfandi bay (SK), a subarctic bay off the town of Húsavík; Eyjafjörður (EY), Iceland's longest fjord, stretching 40 NM from its mouth to the city of Akureyri; and Grímsey (GR), an island at the area's

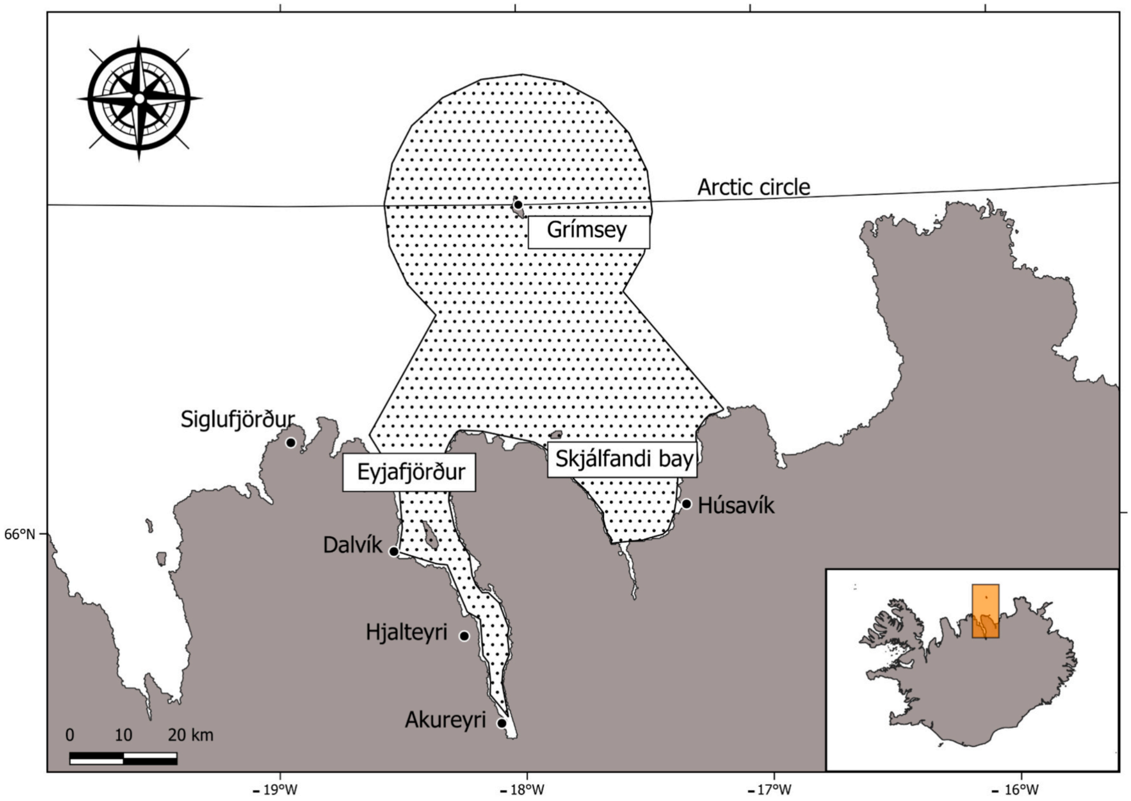

Fig. 1. Map of the Northeast Iceland Hope Spot in the Northeast region of Iceland. The map shows the towns (black dots), and the three M/MP sampling sites (in white boxes).

northernmost tip. This area has traditionally marked the boundary for crossing the Arctic Circle between the North Atlantic Ocean and the Greenland Sea. The marine ecosystems of Northeast Iceland are strongly influenced by the warm North Icelandic Irminger Current (NIIC), part of the North Atlantic Current, which flows northward through Denmark Strait and clockwise around Iceland, where it meets the cold East Icelandic Current (EIC), which flows southward from East Greenland. These two main currents merge into a long current that brings cold and productive waters to northeast Iceland (Casanova Masjoan et al., 2020; Semper et al., 2022) (Fig. S1). In addition, nearshore oceanographic variations can result from river discharge, tides, and underwater topography (Óskarsson et al., 2009).

2.2. Citizen science training

This study was led by experts and scientists from *Ocean Missions*, a local non-profit organization based in Húsavík that combines research and citizen science to inspire and engage people in marine conservation. The team organizes at least two dedicated week-long citizen science expeditions each year in Icelandic waters aboard the S.V. Schooner Ópal. The vessel is provided by *North Sailing*, one of the local whale-watching companies in Húsavík, thanks to a successful collaboration between the two partners. In addition to these sailing expeditions, from 2020 they run a weekly, short (3.5-4 h) citizen science tour called “Whales, Sails and Science” in Skjálfandi bay during the summer months (June–August) and one three-day citizen science tour in the Hope Spot area called “Sailing the Edge of the Arctic” (SEOA). Marine enthusiasts and tourists join the trips and participate in the data collection under the supervision of the expert team. Furthermore, two university students (with previous experience in marine-related fields) are hosted in Húsavík every season and are rigorously trained specifically for sampling during these tours. Their tasks include preliminary visual identification of the suspected M/MP particles, data entry, and sample storage according to the latest guidelines of the Arctic Monitoring and Assessment Program for microplastics and litter in the Arctic (Farmen et al., 2021).

2.3. Sample collection

Fifty-eight trawls were conducted in the Northeast Iceland Hope Spot during the years 2019 — 2023, using standardized methods for monitoring floating M/MP (GESAMP, 2019). Trawling was carried out during nine “one-week-long” dedicated citizen science expeditions (five in spring and four in fall), using a custom-built low-tech aquatic debris instrument (LADI) (Liboiron, 2016) (Fig. S2a). During 2021–2023, an all-purpose velocity accelerated net instrument (AVANI), originally developed by the 5 Gyres Institute (Eriksen et al., 2018) (Fig. S2b), was used to conduct trawls during 3.5–4 h weekly whale watching trips from June through August, in Skjálfandi bay. Both trawls are made with the same 333-μm mesh and are considered accessible and acceptable scientific tools for estimating M/MP (0.3-10 mm in size) concentrations in surface waters (Bashir and Hashmi, 2022; Nousheen et al., 2022).

The LADI was deployed from the vessel's side, traveling at a speed of ≤ 3 knots, in sea states of <3 on the Beaufort scale. To increase the accuracy of abundance estimates, three replicate trawls were conducted in each location with the LADI following a novel zig-zag pattern (30 min per sample) as described in Ovide et al. (2022). While trawling for M/MP is typically done in a straight-line pattern, we found that following a zig-zag pattern was also an effective method of collecting samples. The average distance traveled was 4.2 NM (7.8 km) per three trawls combined. The AVANI design allows sailing speeds of up to 8 knots in moderate seas and was therefore used in linear transects of approximately 30 min, covering an average distance of 4.8 NM (9 km) per trawl. Coordinates for the start and end of each trawl were obtained from the ship's Global Positioning System (GPS). The distance traveled was calculated using the speed over ground (SOG) from the onboard instrumentation. The environmental conditions (wind force and sea state while trawling) were recorded accordingly (Table S1 – Supplementary material).

2.4. Microplastic identification

Preliminary visual identification of M/MP was performed following the GESAMP (2019) guidelines for monitoring plastic litter in the ocean, which are widely used and recognized by national and regional bodies at the EU level (Watson-Wright et al., 2024). Samples were first filtered through two sieves (0.355- and 0.999-mm stainless steel mesh). Visually identifiable plastic particles were selected while biological material (e.g., algae, plankton, feathers) was discarded. Visual identification was performed using a stereomicroscope, and the "hot needle test" based on De Witte et al. (2014) was applied to suspect particles to differentiate between plastic and non-plastic items. The suspected plastic particles were sorted into two main categories: mesoplastic (5–10 mm) and microplastic (0.33 mm–5 mm), using a 5 mm measuring grid. The particles were then classified into five categories: lines, fragments, films, foams, and pellets, following previous studies (Eriksen et al., 2014b). All the samples were counted, measured, and stored in small paper envelopes (Baldwin et al., 2016).

2.5. Contamination control

Sample contamination was considered and minimized at each step. Citizen scientists wore natural fiber clothing. Non-shedding ropes were used to attach the trawl. The complete categorization of the samples was done only by supervised students in a dedicated room, performing one sample blank for each trawl ($n = 58$) and under a 7×-45× Dual Lit 6 W LED Trinocular Stereo Zoom Microscope (SKU: SM-2T-6WB-V331). Only particles visible to the naked eye (larger than 1 mm) were included in the spatiotemporal distribution analysis and spectrometric identification, to minimize the potential risks of the citizen science approach. "Possible boat paints" (Pbp) was added as an additional category to avoid potential contamination from our boat. This last category accounted for paint flakes that matched the color of the Ópal's hull (olive green) and deck (plain white) and were not included in the distribution analysis but were submitted for spectrometric identification (counts and spectra are available in Fig. S3 in the Supplementary material). For the attenuated total reflection–Fourier-transform infrared (ATR–FTIR) and Raman spectroscopy analysis, cotton laboratory coats and clothing were worn in the laboratory. Procedural blank samples were performed daily ($n = 29$) at the laboratory during the spectrometric analysis, and processed by visual identification following the most recent quality assurance and quality control (QA/QC) recommendations (Munno et al., 2023), to detect potential sources of contamination (presence of particles >1 mm).

2.6. Polymer characterization

To confirm that the suspected particles ($n = 481$) were indeed plastic particles and to add a level of polymer identification, polymers from the first sample slot (years 2020 and 2021) were characterized using a higher resolution micro-Raman spectrometer (HORIBA Scientific) in collaboration with the marine biotechnology company *BioPol* at the Technology Centre laboratory in Reykjavík, Iceland (https://taeknisetur.is). The parameters used for the Raman were 25 % laser intensity, wavelength 500 nm x magnitude coefficient x50. For the second data slot (years 2019, 2022, and 2023), Fourier-transform infrared spectroscopy was used in the laboratory of the Department of Science and Environment at the University of Roskilde, Denmark. In this case, a PerkinElmer Spectrum Frontier spectrometer with a single bounce diamond/ZnSe internal reflectance element (2 × 2 mm) was used to perform accumulated scans per particle at a force gauge of 60 % and a resolution of 2 cm^{-1} between 4000 and 600 cm^{-1}.

The spectra acquired by ATR-FTIR were converted into .csv files using the instrument software and the free software Spectragryph (version 1.2) for micro-Raman (Menges, 2022). The files were then compared with dedicated databases for the ATR-FTIR spectra (Simon-Sánchez et al., 2024) and for the Raman spectra (Maurizi et al., 2024) using the free software siMPle (Primpke et al., 2020). Polymer characterization was based on a 70 % confidence level, which was consistent with the reference spectra for ATR-FTIR, following previous studies (e.g., Lusher et al., 2013). For Raman, a lower value (>50 %) was used to account for uncertainty in particle detection, following the recommendations of Maurizi et al. (2024). Each particle was weighed using a microbalance (*Mettler Toledo*; range 1.0–5000 mg).

2.7. Statistical analysis

M/MP abundance was expressed per volume as particles/m^3 as the primary unit of measure using the formula:

$$\begin{aligned}\text{Particles per m}^3\text{ of sea surface} = {} & \text{total number of plastic particles} \\ & /\text{distance towed }(\text{m}) \times 0.5 \\ & \times \text{trawl opening area }(0.34 \\ & \times 0.34\text{ in LADI}; 0.6 \times 0.1\text{ in AVANI})\ (\text{m}^2).\end{aligned}$$

The factor of 0.5 was applied to account for the fact that only the lower half of the trawl opening was submerged during sampling (Baldwin et al., 2016; Gewert et al., 2017).

To increase comparability with other studies worldwide, M/MP abundance was also expressed in particles/km^2 by applying the widely used equation (e.g., Collignon et al., 2012; Gewert et al., 2017) and adopted by Ovide et al. (2022) and Clark et al. (2023):

$$\begin{aligned}\text{Particles per km}^2\text{ of sea surface} = {} & \text{total number of plastic particles} \\ & /\text{distance covered} \\ & \times \text{trawl opening width }(\text{km}).\end{aligned}$$

$$\begin{aligned}\text{Trawl opening width LADI} = 0.00034\text{ km}; \text{ trawl opening width AVANI} \\ = 0.000165\text{ km}.\end{aligned}$$

To compare M/MP variability between trawls, the distance and number of M/MP particles were summed for the three transects for the LADI sampling, and average particles/m^3 were calculated for each sampling (Table S2 in the Supplementary material). Lastly, we analyzed the influence of wind force and sea state, as defined by the Beaufort scale, on meso- and microplastic occurrence in our dataset.

Data analysis was performed using *IBM SPSS Statistics 2023* (version 29.0.2.0). Due to the small sample size and non-normal distribution of the data, non-parametric tests were used to analyze the data. The Independent-Samples Kruskal-Wallis test was chosen to assess the spatial variation of meso- and microplastic abundance between sampling sites and the temporal variation across years and months for the Hope Spot area, which includes all three sampling sites. In addition, the same analysis was repeated for Skjálfandi bay alone, as this was the most extensively sampled site. Lastly, the independent samples Mann-Whitney U test was performed to assess differences in M/MP abundance between trawling environmental conditions and the two trawl types (LADI vs. AVANI).

3. Results

3.1. Presence, distribution, and abundance of meso- and microplastics

No M/MP (>1 mm) were detected in any field blank during the sampling. Four fibers (<1 mm) were found in the field blanks and two in the procedural blanks, all of which were cellulose. This suggests minimal M/MP contamination risk during our sampling and processing.

Mesoplastics (5–10 mm) and microplastics (0.33 mm–5 mm) were present in 86 % of the trawls ($n = 58$) from the three sampling sites and over a total distance of 511 km (275.6 NM). Of the 426 items (excluding Pbp), 188 (44 %) were mesoplastic particles, and 238 (56 %) were microplastics. The average estimated volumetric abundance of M/MP for all the trawls combined was 0.02 ± SD 0.03 particles/m^3 (CI (95 %) = 0.007), 4600 ± SD 6300 (range 0–38,400) particles/km^2(CI (95 %) = 1600), and 0.005 ± SD 0.006 particles/m^2 (CI (95 %) = 0.002). An overview of M/MP abundance per sample is provided in Table S3, Supplementary material.

The average M/MP abundance in the three sampled sites was highest at Grímsey ($n = 5$) (0.070 SD ± 0.03 particles/m^3; 13,100 SD ± 6500 particles/km^2, min. 500, max. 38,400, CI (95 %) = 5700), followed by Eyjafjörður ($n = 4$) (0.006 SD ± 0.04 particles/m^3; 5400 SD ± 5500 particles/km^2, min. 2800, max. 11,000, CI (95 %) = 5500), and Skjálfandi bay ($n = 49$) (0.0042 SD ± 0.03 particles/m^3; 3600 SD ± 5400 particles/km^2, min. 0, max. 22,800, CI (95 %) = 1500) (Figs. 2 and 3). M/MP concentrations across the locations are expressed in different metric units to allow comparison with other studies (Fig. S4 and Table S4).

The Independent-Samples Kruskal-Wallis test indicated a statistically significant difference in M/MP concentration between the three sampling sites (H = 10.613, df = 2, $p = 0.005$). Pairwise comparisons revealed a significant difference in M/MP/m^3 between Skjálfandi bay and Grímsey, with an adjusted p-value of 0.024, suggesting a notable disparity between the two sites, with Grímsey showing higher contamination levels. The comparison between Skjálfandi bay and Eyjafjörður also showed some degree of difference, as indicated by an initial p-value of 0.031. However, this difference was not statistically significant after applying the Bonferroni correction for multiple comparisons (adjusted p-value = 0.093). In contrast, no significant difference was found between Grímsey and Eyjafjörður (adjusted p-value = 1.000).

3.2. Temporal distribution of meso- and microplastics

Temporal trends were investigated for the Northeast Iceland Hope Spot, combining the three sampling sites, and then specifically in Skjálfandi bay, with the highest number of data samples, to increase the resolution of the results for further interpretation (Table 1).

For the entire Northeast Hope Spot area (three sampling sites combined), M/MP abundance was compared across years (2020−2023) and months (May, June, July, August, and September) to explore temporal trends. The year 2019 ($n = 1$), and the months April ($n = 1$) and October ($n = 2$) were not included in the comparison due to the small sample size ($n \leq 3$). When comparing the variance between years, the highest mean concentration of M/MP was observed in 2023 ($n = 15$), with a mean of $\bar{x}$= 0.03 particles/m^3 (6200 SD ± 10,500 particles/km^2), followed by 2022 ($n = 17$) with a mean of $\bar{x}$= 0.02 particles/m^3 (5600 SD ± 4600 particles/km^2). In 2021 ($n = 21$), the mean was $\bar{x}$= 0.01 particles/m^3 (2700 SD ± 3500 particles/km^2), while in 2020 ($n = 4$), the mean was $\bar{x}$= 0.02 particles/m^3 (3529 SD ± 2100 particles/km^2).

A Kruskal-Wallis test indicated that although the mean M/MP/m^3 abundance appeared to increase from 2020 to 2023, the differences were not statistically significant (H = 6.928, df = 3, $p = 0.074$) (Fig. 4a). Although not meeting the conventional threshold for significance the trend suggests that there may be some underlying variation that requires further investigation.

The variance analysis of M/MP between months showed slightly higher microplastic concentrations in June ($n = 21$; $\bar{x}$= 0.03 particles/m^3 (5900 SD ± 9073 particles/km^2)), followed by September ($n = 5$; $\bar{x}$= 0.03 particles/m^3 (5500 SD ± 4100 particles/km^2)), July ($n = 14$; $\bar{x}$= 0.02 particles/m^3 (4200 SD ± 5800 particles/km^2)) and then August ($n = 11$; $\bar{x}$= 0.01 particles/m^3 (4200 SD ± 6200 particles/km^2)). Despite the higher concentration in June and September, the Kruskal-Wallis test showed no statistically significant differences in M/MP/m^3 between the months (H = 3.476, df = 4, $p = 0.482$) (Fig. 4b), and seasons (Table S5).

In an attempt to minimize the uncertainty of the intrinsic variation of M/MP, differences in distribution across years (2021−2023) and months (June–August) were further investigated in Skjálfandi bay, where the sampling effort was significantly higher than the other sampling sites ($n = 49$) – one trawl event per week from June to August for three consecutive years (2021–2023) (Fig. 5).

Mean M/MP abundance was highest in 2022 ($n = 15$): $\bar{x}$= 4800 SD ± 4200 particles/km^2; 0.02 particles/m^3, followed by 2023 ($n = 13$): $\bar{x}$= 4000 SD ± 6000 particles/km^2; 0.01 particles/m^3, and then 2021 ($n = 19$): $\bar{x}$= 2300 SD ± 3200 particles/km^2; 0.007 particles/m^3. However, a Kruskal-Wallis test showed no statistically significant difference in abundance between years (H = 1.036, df = 2, $p = 0.596$).

The mean values of M/MP concentrations for each month, from highest to lowest, were as follows: August ($n = 12$): $\bar{x}$= 0.01 particles/m^3 (4000 SD ± 5000 particles/km^2), June ($n = 17$): $\bar{x}$= 0.01 particles/m^3 (3400 SD ± 4600 particles/km^2), July ($n = 15$): $\bar{x}$= 0.01 particles/m^3 (3300 SD ± 4700 particles/km^2).

Similarly, the Kruskal-Wallis test showed no statistically significant differences in abundance between the months (H = 1.000, df = 2, $p = 0.606$).

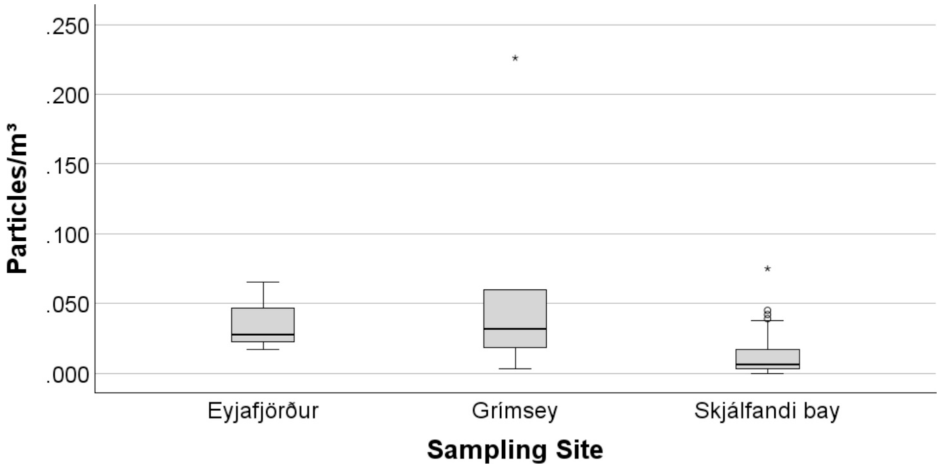

Fig. 2. The abundance of meso-and microplastics (particles/m^3) per sampling site: Eyjafjörður (EY), Grímsey (GR), and Skjálfandi bay (SK). Number of trawls: $n = 4$ (EY), $n = 5$ (GR), and $n = 49$ (SK). The horizontal black lines represent the median values. The box shows the first and third quartiles, the whiskers show the minimum and maximum values, and outliers are shown individually (°;*).

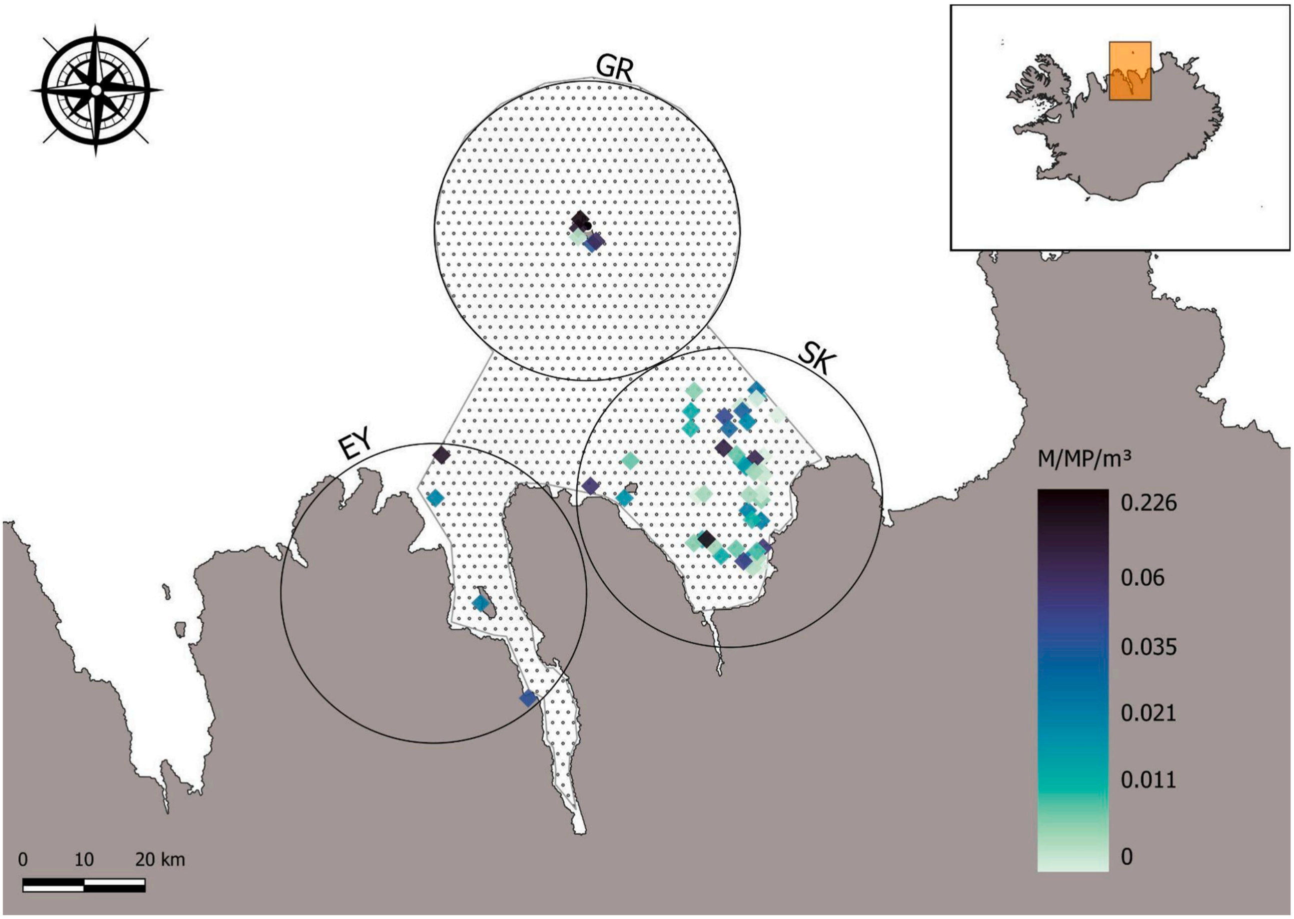

Fig. 3. Spatial distribution map of meso- and microplastic abundance per location (Eyjafjörður (EY), Grímsey (GR), Skjálfandi bay (SK) per trawl, expressed in particles (M/MP)/m^3.

3.3. Variation between environmental conditions and trawl types

We examined whether wind force and sea state during trawling influenced the occurrence of meso- and microplastics in our dataset. No significant differences were observed. (Fig. 6).

Additionally, we examined the meso- and microplastic concentrations between trawl types. The mean M/MP/m^3 for the LADI trawl combining the three sampling sites was $\bar{x}= 0.01$ particles/m^3 (8700 SD ± 6500 particles/km^2; min. 467, max. 38,400; CI (95 %) = 1900); and for AVANI trawl was $\bar{x}= 0.01$ particles/m^3 (3800 SD ± 6700 particles/km^2; min. 0, max. 26,180; CI (95 %) = 3800). Of the 58 trawls conducted, 11 used the LADI trawl with a total distance of 83 km, while 47 trawls used the AVANI trawl with a total distance of 426 km. In Eyjafjörður, four out of four trawls were conducted with the LADI trawl, and in Grímsey four out of five trawls were conducted with the LADI trawl. In Skjálfandi bay three trawls were conducted with the LADI trawl while 46 trawls were conducted with the AVANI trawl. The statistical comparison in Skjálfandi bay revealed no significant differences in M/MP/m^3 concentrations collected by the two types of trawls (Mann-Whitney U = 107.5, $p = 0.113$, $N = 49$). (Fig. S5).

3.4. Meso- and microplastic categorization

Visual identification and categorization revealed that out of a total of 481 M/MP particles, “lines” were the most common type with 44 % ($n = 211$), followed by “fragments” with 33 % ($n = 161$); “possible boat paints” (Pbp) with 11 % ($n = 55$); “films” with 10 % ($n = 46$), “foams” with 1 % ($n = 6$) and “pellets” with only 0.4 % ($n = 2$) (Figs. 7 and S6).

Out of 211 “lines,” 199 (41 %) were categorized as “filaments” (likely from fishing) and only 12 as “fibers” (likely from textiles), following the recommendations of GESAMP. (2019) to more accurately categorize the origin of the particles.

3.5. Spectroscopic results: types of polymers

All the visually identified particles ($n = 481$) were subjected to weight measurements and spectroscopic analysis for polymer identification. The mean particle weight was 3.4 mg. Of the 481 total particles, 415 could be verified using FTIR or Raman techniques. The remaining 66 particles broke or were not found during sample handling (Table 2).

Overall, the results of the spectroscopic analysis were used to classify the particles into four categories: “plastics”, “natural”, “n.d” (not detected), and “others”. The results showed that 337 particles were “plastic”; 54 particles were “natural” (e.g., natural fibers such as cotton), 20 were n.d, and 4 were categorized as “others”. The “others” category includes particles that don't have the characteristics of plastic but are derived from anthropogenic sources (e.g., rubbers and resins) (Fig. 8). The results of FTIR and Raman are presented separately in Table S6).

The analysis identified 15 polymer types, with polyethylene (47 %, $n = 159$) and polypropylene (39 %, $n = 133$) being the most prevalent, followed by alkyd (4 %, $n = 12$) (Table 3; Fig. 9). Table S7, which is included in the supplementary material, presents the concentrations of particles for each polymer type, reported as particles/m^3 and particles/km^2.

To trace the origin of suspected green and white paint particles in our samples, we compared green and white flakes from the platform vessel “Opal” with “possible boat paint” particles (green and white) from our dataset. The spectrometric analysis identified the vessel's paint as PVOH

Table 1
Meso and microplastic abundance in the Northeast Iceland Hope Spot and Skjálfandi bay: Annual and monthly means (x̄, particles/km^2 and particles/m^3), with standard deviations (SD), confidence intervals (CI), min and max (particles/km^2).

Northeast Iceland Hope Spot

Year	n trawls	x̄= Particles/ km^2 (m^3)	SD	CI (95 %)	min	max
2020	4	3529 (0.02)	2200	2100	2100	6700
2021	21	2700 (0.01)	3500	1509	0	12,700
2022	17	5600 (0.02)	4600	2200	890	13,600
2023	15	6200 (0.03)	10,500	5300	0	38,400

Months	n trawls	x̄= Particles/ km^2 (m^3)	SD	CI (95 %)	min	max
May	5	1900 (0.006)	4100	3600	0	3600
June	21	5900 (0.03)	6400	2700	0	38,400
July	14	4100 (0.02)	5800	3038	0	22,700
August	11	4200 (0.01)	6200	3664	0	12,700
September	5	5500 (0.03)	4100	3600	470	11,000

Skjálfandi bay

Year	n trawls	x̄= Particles/km^2 (m^3)	SD	CI (95 %)	min	max
2021	19	2300 (0.007)	3200	1400	0	12,700
2022	15	4800 (0.02)	4200	2100	900	13,600
2023	13	4000 (0.01)	6000	3200	0	22,800

Months	n trawls	x̄= Particles/km^2 (m^3)	SD	CI (95 %)	min	max
June	17	3400 (0.01)	4600	2299	0	13,700
July	15	3333 (0.01)	4700	2400	0	22,800
August	12	4000 (0.01)	5000	2900	9	12,700

and/or polyethylene, though low match scores (0.4–0.7) resulted from Raman reacting to white and green pigments over polymer type. The "possible boat paint" particles were identified as 67 % polyethylene, 8 % alkyd, 17 % acrylic, and 8 % antifouling paint.

3.6. Assessment of the citizen data

To assess the validity of the citizen science approach, we compared our data collected by citizen scientists to other studies conducted by experts, who also used towable nets (>333 μm) to survey floating M/MPs in the Arctic regions. The purpose of this comparison is to determine the extent to which the citizen-generated data meets scientific standards (Table 4).

In this study, the observed differences are consistent with those reported in previous studies. M/MP concentrations in the Northeast Iceland Hope Spot (0.02 ± SD 0.03 (0–0.23) particles/m^3; 6000 ± SD 5100 (0–38) particles/km^2) are lower than those in Svalbard (0.34 ± SD 0.31 particles/m^3), the Kara Sea (0.31–0.92 particles/m^3), the White Sea (0.19–1 particles/m^3), the Baltic Sea (0.2 ± 0.2 (0.3–2.1 particles/m^3) and the Chukchi Sea (0.23 ± 0.07 (0.086–0.31) particles/m^3), but higher than those in the Eurasian Arctic (0.004 (0–2.4) particles/m^3) and the Laptev Sea (0.002 particles/m^3). The averages are comparable to those reported for the East Siberian region (0.01 particles/m^3) and the Beaufort Sea (7.5 ± SD 7.6 (0.9–28) particles/km^2).

4. Discussion

4.1. Heterogeneous distribution

Overall, the results highlight the heterogeneous distribution of meso- and microplastic concentrations between sampling sites, with notable differences between Skjálfandi bay and Grímsey. Contrary to our expectations, waters surrounding Grímsey, a remote island located 21 NM from the nearest spot in the mainland, had significantly higher M/MP concentrations. Skjálfandi bay and Eyjafjörður, with larger towns along the shores and higher boat traffic, had lower concentrations. The elevated microplastic concentrations observed in nearshore Grímsey surface waters could be influenced by the North Icelandic Irminger Current, which moves clockwise around North Iceland transporting nutrients and contributing to local upwelling events (Semper et al., 2022). This current may also disperse pollutants to remote areas, as previously observed by Loughlin et al. (2021). However, the transport and fate of buoyant particles at the surface are primarily influenced by mechanisms such as Ekman drift, windward drift, and Stokes drift, which are driven by wind and wave conditions. Despite this understanding, there is a significant gap in our knowledge of the physical processes that govern the movement of plastic particles in coastal seas. Comprehensive studies examining the combined effects of hydrodynamic factors (e.g., wind, waves, tides, and salinity), depositional environments (such as shoreline features, coastal geomorphology, and benthic sediments), and microplastic characteristics (e.g., density and size) are still lacking (Browne et al., 2010). Therefore, further research (e.g., integration of microplastic distribution models with local oceanographic and meteorological models) is needed to identify and analyze underlying trends for the study area.

Potential local sources of meso- and microplastics in the Northeast Iceland Hope Spot include the fishing village of Grímsey (population 57), nearby towns such as Akureyri and Húsavík (population 19,800 and 2300), and larger urban areas like Reykjavík (population 136,800) (Statice, 2024). Additionally, it is vital to investigate whether microplastics are entering the marine environment via the main rivers that flow into Skjálfandi bay (Skjálfandafljót glacier river and Laxá River). Moreover, the distribution of meso- and microplastics in the Northeast Iceland Hope Spot can also be impacted by transportation processes over long distances via major ocean currents, including branches of the Gulf Stream. Atmospheric transport is another important pathway, with strong winds resuspending meso- and microplastic particles into the air from land and marine surfaces and facilitating secondary transport. This process greatly increases the efficiency of airborne dispersal to distant regions, such as the Arctic. For example, wind and precipitation are major contributors to microplastic deposition in the Vatnajökull ice cap in Iceland (Stefánsson et al., 2021). Another potential explanation for the presence of M/MP in Iceland's coastal ecosystems may be the lack of efficient wastewater management facilities, which currently don't account for the infrastructure to prevent contamination (UNAK, 2021). In this context, meso- and microplastic monitoring in nearshore marine sites within the Northeast Iceland Hope Spot serves as a valuable initial dataset for understanding their distribution patterns.

As expected, the concentration of particles over years and months was not statistically significant, suggesting a homogeneous temporal occurrence of meso- and microplastics. However, the relatively high variation (±SD values and confidence intervals) across sites, years, and months, is likely a consequence of the inherent heterogeneity of meso- and microplastics (Kye et al., 2023), especially in Arctic environments where weather conditions are more extreme (Ólafsson et al., 2007). Furthermore, the limited number of samples in this study may compromise the statistical power, masking significant spatial and temporal patterns and potentially leading to under- or overestimation of M/MP concentrations.

4.2. Environmental conditions and sampling challenges

As noted above, dynamic physical processes such as strong wind, waves, and ocean currents, influence the horizontal transport and vertical displacement of meso-and microplastics on the sea surface, resulting in variability in local plastic concentrations. To minimize variability, ancillary data (e.g., wind speed) were recorded during sampling, and sampling was avoided in conditions above Beaufort Sea State 3, following the recommendations of Martin et al. (2023). The lack

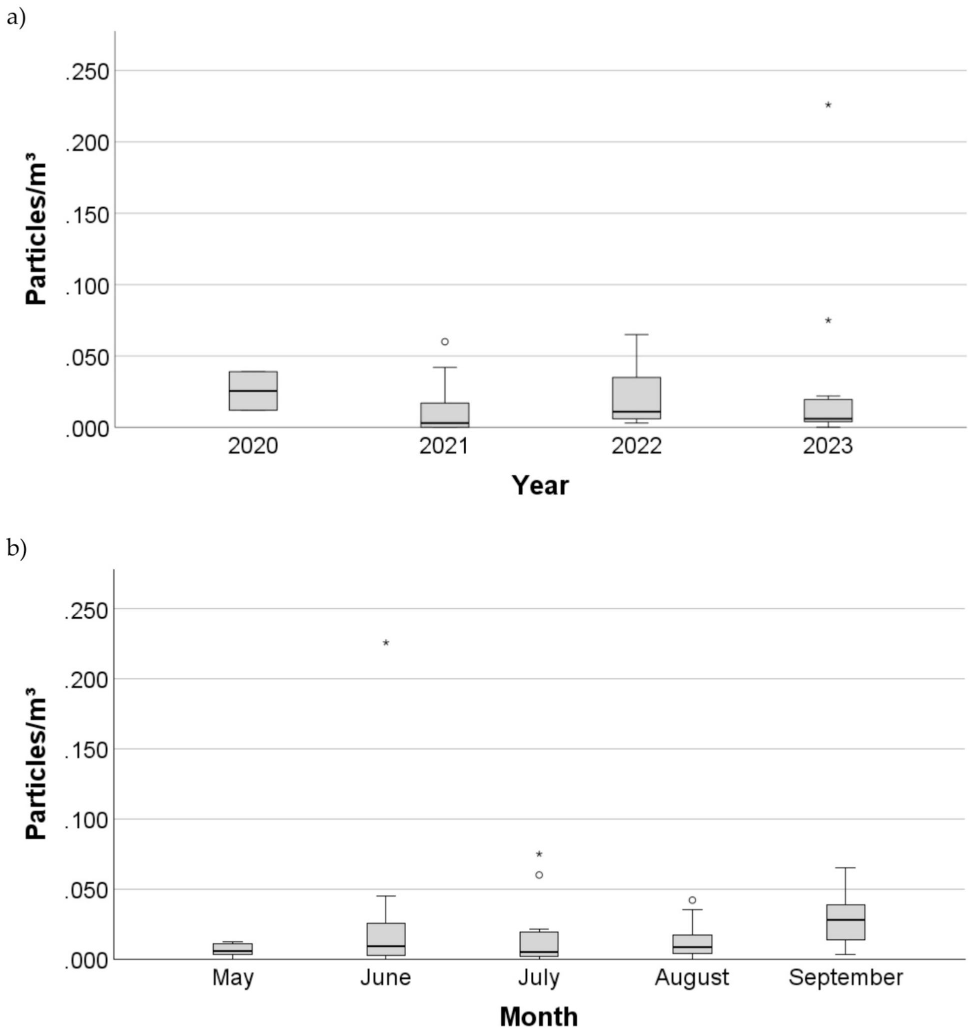

Fig. 4. Box plots showing microplastic abundance (particles/m^3) in the Northeast Iceland Hope Spot across (a) years (2020–2023) and (b) months (May, June, July, August & September) for the three sampling sites combined.

of correlation ($p = 0.4$) between wind strength and sea state (while trawling) on the abundance of meso- and microplastics, indicates that there is insufficient evidence to state that wind strength and sea state alone influence the presence and abundance of M/MP. However, it is also important to consider weather conditions before trawling (e.g., events like a major storm the day before could potentially concentrate plastics in specific areas). In addition to the inherent distribution patterns of meso- and microplastics in aquatic systems, it is well-established that mixing processes within surface layer convergence zones can significantly influence the vertical distribution and accumulation of particles (Enders et al., 2015). Additional data collection using a CTD (Conductivity, Temperature, and Density) and chlorophyll measurements could provide complementary information on water conditions and aid in the interpretation of variability trends. Integrating these data with existing models, such as those shown by Wu et al. (2024), could improve understanding of meso- and microplastic distribution, although such models do not yet exist for Iceland's coastal ecosystems.

4.3. *Most prevalent meso- and microplastic categories and polymers*

"Filaments" likely originally derived from fishing gear, also referred to as "threads" by Saturno et al. (2020), constituted the dominant type of M/MP (41 %). These results are consistent with the expected results as Iceland is historically a fishing nation. These results are not surprising, considering that discarded fishing equipment or "ghost" fishing gear (mainly nets and ropes) accounts for 46 % to 70 % of all marine debris by weight, worldwide (Loprespub, 2020). In fact, these results are in line with the recent findings from beach cleanup efforts in Northeast Iceland, where nets are the largest category by volume (Ocean Missions, 2024). Furthermore, in nearby Greenlandic waters, Liboiron et al. (2021) identified filaments as the second most prevalent type of plastic in subsurface waters, accounting for 26 %. The second dominant category in this study was "fragments" at 33 %, although their origin remains undetermined.

PE and PP were the most abundant polymer types and agreed with the expected results. Similarly, PE (30 %) and PP (19 %) were the most commonly produced plastic polymers worldwide, according to Bråte et al. (2014) and Miranda-Peña et al. (2023), who also reported PE (28 %) and PP (24 %) as the predominant microplastic contaminants in surface waters in lentic ecosystems. Furthermore, Geyer et al. (2017) reported that the largest microplastic non-fibrous groups worldwide were PE (36 %, $n = 159$) and PP (21 %, $n = 131$). These results are in accordance with previous studies conducted in the Arctic. For example, Liboiron et al. (2021) reported PE (21 %, $n = 8$) as the most dominant polymer type, followed by epoxy blends (18 %, $n = 7$), and polystyrene (15 %, $n = 6$) in Greenland seawater. These polymer types are usually plastic blends widely used in packaging, construction, and fishing gear.

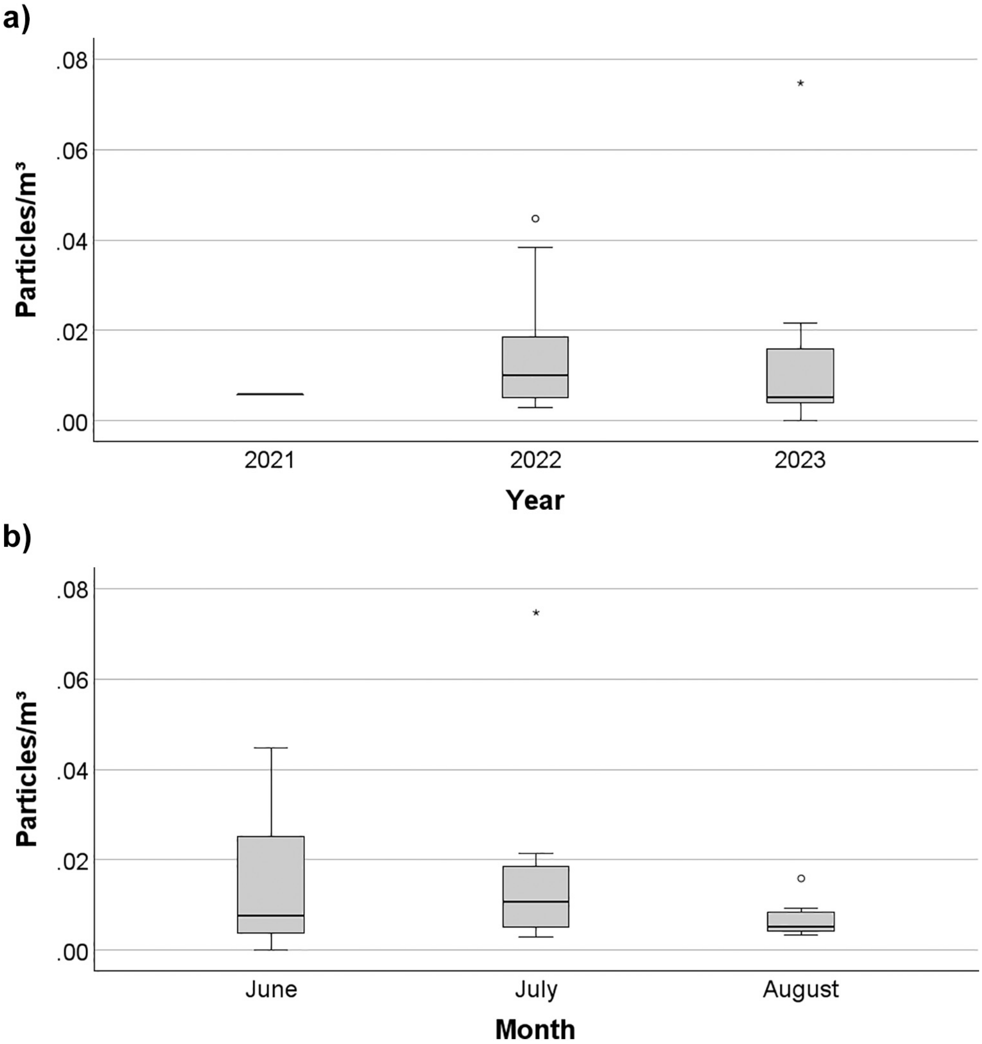

Fig. 5. Box plots showing the abundance of M/MP (particles/m^3) in Skjálfandi bay over (a) years (2021–2023) and (b) months (June, July, August).

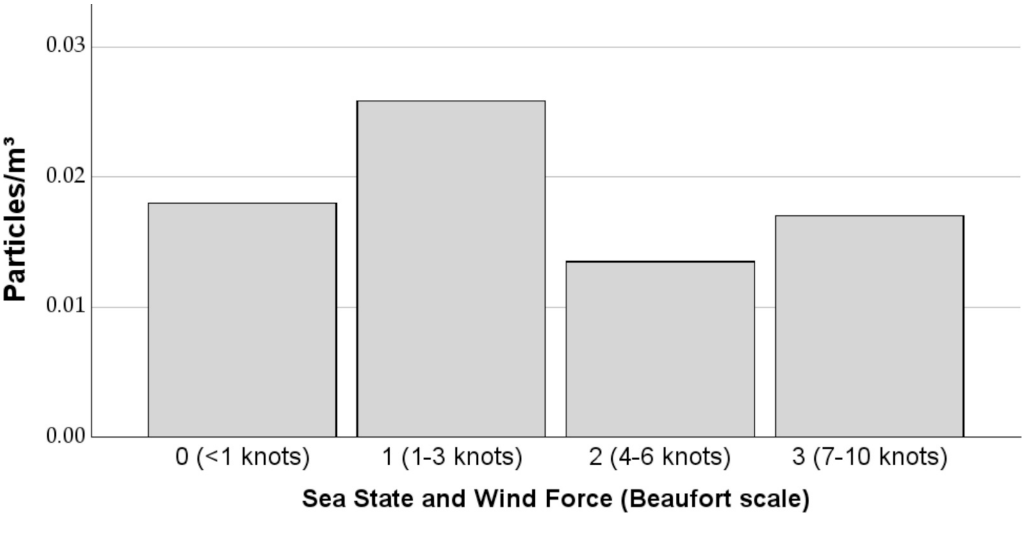

Fig. 6. Relationship between meso- and microplastic (M/MP) abundance and environmental conditions. M/MP concentrations are represented in the y-axis. Sea state and wind force (in knots) in the x-axis, as characterized by the Beaufort scale.

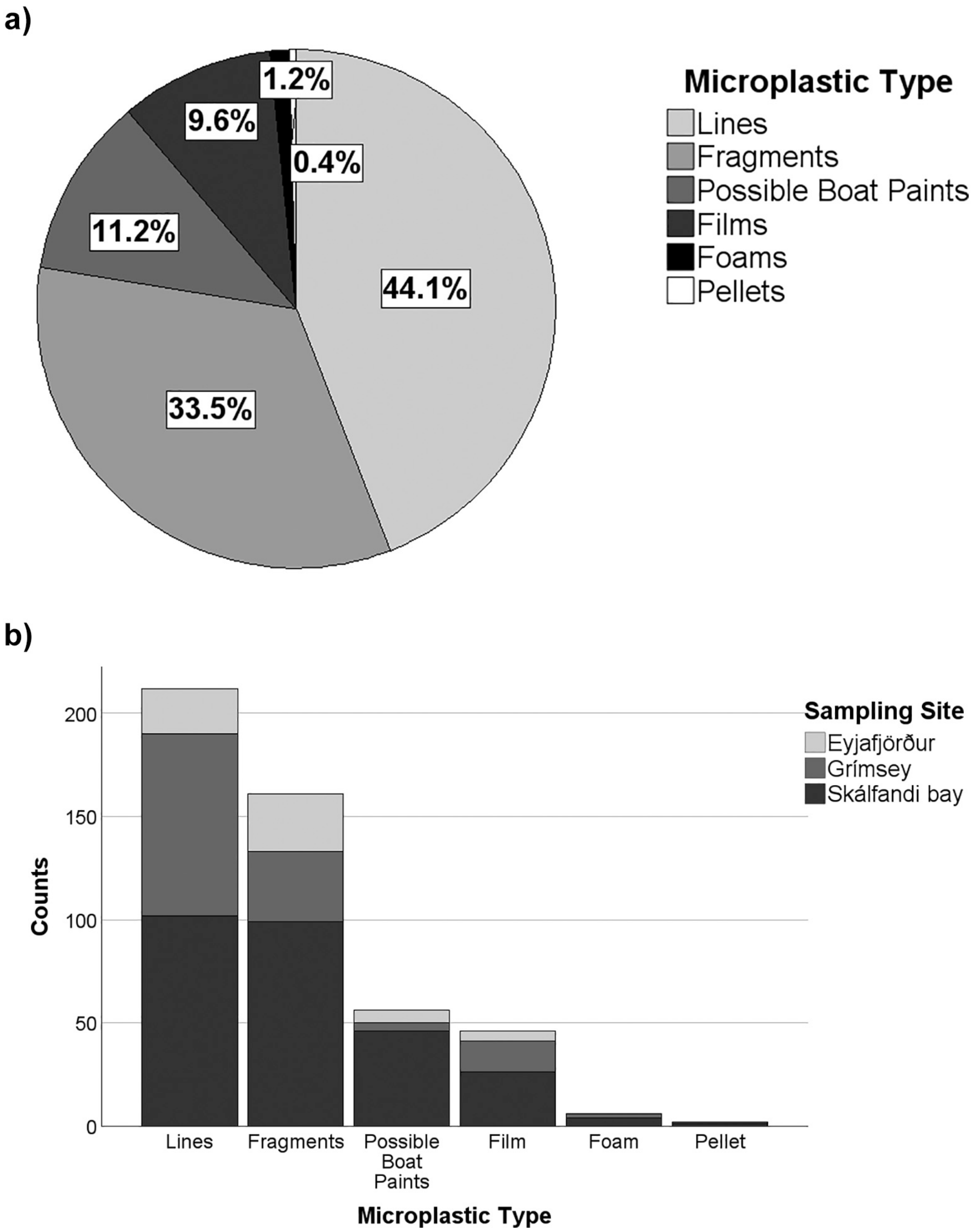

Fig. 7. (a) Pie chart showing the total percentage of M/MP type, and (b) bar chart showing the types of M/MP found at the three sampling sites: Eyjafjörður (EY), Grímsey (GR) and Skjálfandi bay (SK).

Table 2
Summary of the particle weight (expressed in milligrams) and concentration by volume of filtered water per site: Eyjafjörður (EY), Grímsey (GR) and Skjálfandi bay (SK), and for all sites combined.

	EY	GR	SK	All combined
n trawls	5	4	49	58
n plastic particles	33	86	296	415
Mass of plastic collected (mg)	122	205	995	1322
Mean particle weight (mg)	2.3	1.8	4.4	3.4
Mean density (particles/m^3)	0.020	0.044	0.044	0.04
Mean density (particles/km^2)	330	8600	3700	4150
Mean mass^2	1220	20,500	12,000	4150

4.4. Implications of paint particles in the samples

The relatively high presence of paint particles (16 %) raises concerns about paint and chemical leakage into marine environments. In 2022, *Earth Action* found that paint contributes more microplastics to the aquatic environment than previously thought, with 58 % of all microplastics coming from paint. The increased boat traffic in Eyjafjörður and Skjálfandi bay, driven by tourism and shipping, may contribute to the shedding of microplastic boat paint particles. Icelandic shipyards with open maintenance areas and insufficient preventive measures to mitigate paint shedding may also contribute. High levels of boat paint particles have been reported in Greenland (Liboiron et al., 2021) and the Baltic Sea (Setälä et al., 2022). Lastly, while spectrometric analysis offered initial insights into the composition of paint particles from the sampling vessel, the low match scores emphasize the limitations of current methods in accurately determining their origin. Future steps

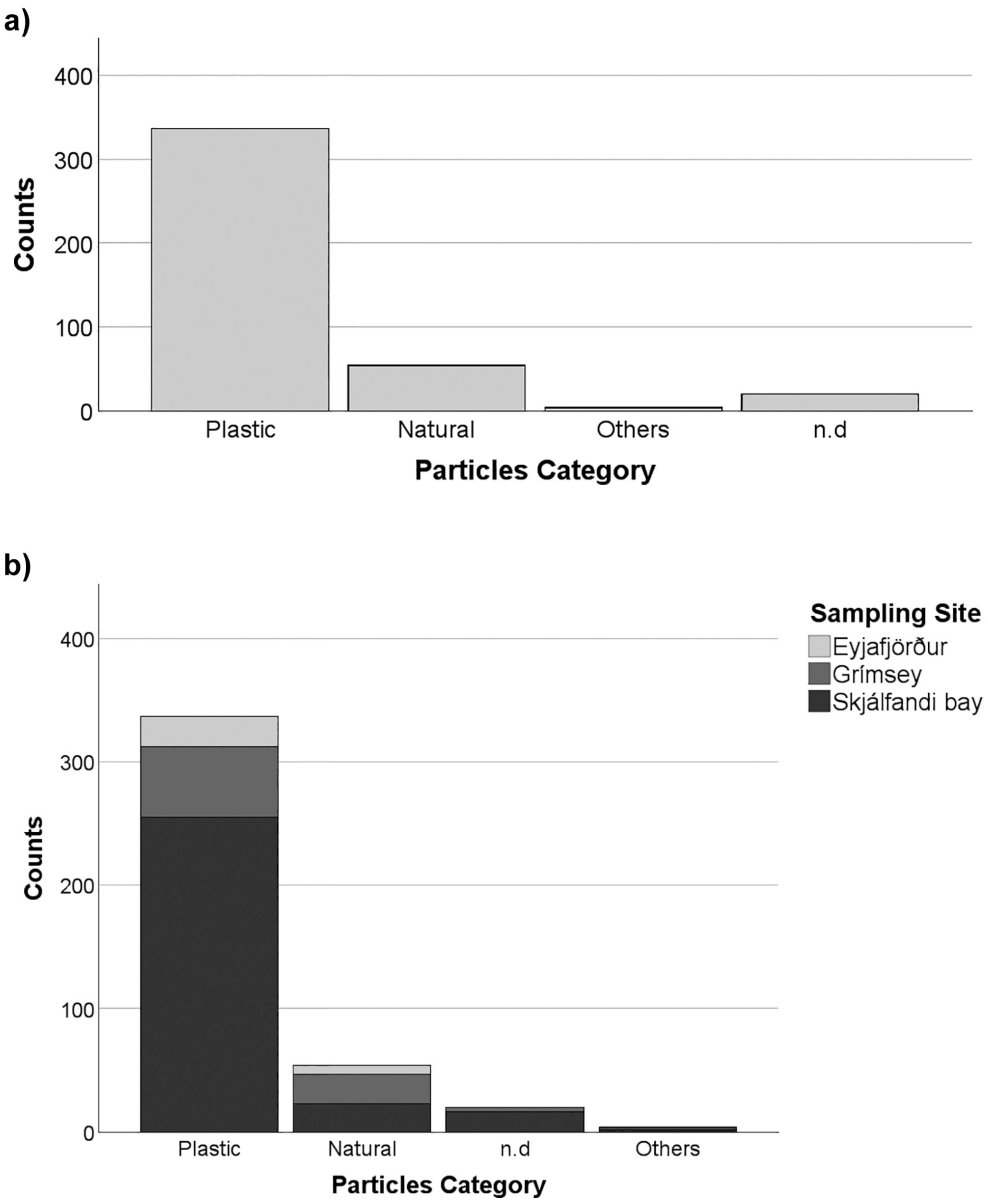

Fig. 8. Particle categorization based on Fourier-transform infrared spectroscopy (FTIR) and Raman spectroscopy, distinguishing between plastic, natural, and other particle types (a). The category "n.d" (not detected) refers to particles that could not be successfully identified. The data are represented for the three sampling sites: Eyjafjörður, Grímsey, and Skjálfandi bay (b).

should account for the potential interference of certain pigments that may obscure particle identification and assess whether or not these particles are contaminating our samples.

4.5. Performance of LADI and AVANI trawls

The similar mean M/MP concentrations when comparing the two types of trawls suggests that it is possible to compare the results if the existing protocols for each device are carefully followed (e.g., by trawling for at least 30 min), as already demonstrated by Eriksen et al. (2018). Both trawl types also have high standard deviation values in common, due to the nature of the M/MP dispersion factors already mentioned in previous studies (Stride et al., 2024). While the high-speed AVANI trawl has the advantage of better performance on opportunistic platforms (trawling speed <8 knots which is often the cruising speed for small boats <20 m), the protocol used for the low-speed LADI trawl (3 zig-zag trawls <3 knots), aims to minimize the uncertainty of the intrinsic variation in meso- and microplastics at localized sampling sites. The higher concentration of M/MP in LADI trawls (8700 particles/km^2) versus AVANI trawls (3800 particles/km^2) could be explained by a larger area (km^2) covered by the LADI in each trawl in combination with the heterogeneous distribution of plastics (Kane and Clare, 2019). Previous studies indicate that the use of GPS points versus a flowmeter to calculate the volume of water filtered by the trawl can lead to different results (Pasquier et al., 2022). For this study, we only used GPS methods because a flowmeter was not available for most of the trawls. However, for data optimization, the use of a flowmeter along with GPS to monitor water flow is recommended. Finally, our study demonstrates that both trawl types are suitable for citizen science-driven monitoring programs. Based on our experience, we recommend using either the LADI or AVANI, depending on the goals of the citizen science project and the logistical considerations of the study area.

Table 3

Particles verified by FTIR and Raman (match scores > 0.7 for FTIR and > 0.5 for Raman; and post-analysis visual verification: polymer types, common applications, average weight, and mean particles/km^2 of each polymer type.* AF (Antifouling).

Type of polymer	Common uses	Counts	%	Average weight	M/MP/km^2
Acrylic paint	Paints and varnishes, furniture and architectural coatings	9	2.7	0.96	90
AF*_paint		2	0.6	0.14	20
Alkyd	Paints, varnishes, coatings anti-corrosive primers	12	3.6	0.14	120
Polyethylene (PE)	Packaging, trash bags, wire and cable insulation	159	47.2	1.94	1590
Polyethylene terephthalate (PET)	Packaging, soda pop bottles, textiles	1	0.3	0.03	10
Polyester	Textiles, bottles resin, and films, mainly for packaging	2	0.6	0.55	20
Polypropylene (PP)	Packaging, textiles, medical applications, fishing gear	133	39.5	4.1	1330
Polystyrene (PS)	Foam packaging and coolers, medical applications	5	1.5	0.63	50
Polyurethane (PUR)	Coatings, spray, and rigid foams. Common in construction.	2	0.6	8.9	20
PU paint		2	0.6	0.92	20
Polyvinyl chloride (PVC)	Piping and siding, tubing, wire and cable insulation	6	1.8	2.39	60
Polyvinyl alcohol (PVOH)	Papermaking, coatings, wrapping	3	0.9	0.44	30
Ship paint		1	0.3	n.a	10

4.6. Optimizing citizen science sampling

Lower confidence intervals in Skjálfandi bay (n = 49; 3600 SD ± 5400 particles/km^2; CI (95 %) = 1500) compared to Eyjafjörður (n = 4; 5400 SD ± 5500 particles/km^2; CI (95 %) = 5500) and Grímsey Island (n = 5; 13,100 SD ± 6500 particles/km^2; CI (95 %) = 5700) suggest that concentrated sampling efforts improve the precision of microplastic estimates. Nevertheless, for future studies, a powerful statistical analysis should be conducted to ensure sufficient sample sizes and increase the reliability of the data and the ability to detect meaningful differences.

A more comprehensive approach to minimizing uncertainty may be to combine trawl surveys with simultaneous sampling at different depths and in sediments, as shown by Setälä et al. (2022). Although logistically complex and costly, multi-matrix methods (e.g., surface and subsurface sampling) have been tested by citizen scientists in areas such as Baffin Island (Martin et al., 2023). Alternatively, using multiple short sampling periods (10 min each) rather than a single long period (30 min) offers a more practical approach with representative results (Pasquier et al., 2022).

Using different sources and protocols can cause inconsistencies in particle categorization and challenges when comparing results across studies. In this study, three microplastics visually identified originating from fishing gear (e.g., ropes, nets) aligned with spectral categorization (PE or PP) but were classified as "fragments" rather than "filaments," following Vianello et al. (2019), who defined filaments as having a width ratio of at least 3:1 (Fig. S7 in the Supplementary material).

4.7. Validation of the citizen science approach

Our observed variations align with the existing literature and similar studies conducted in other Arctic regions. Our results suggest that the estimations in M/MP abundance on the sea surface are lower in the Northeast Iceland Hope Spot (0.02 ± SD 0.03 particles/m^3; 0.005 ± SD 0.006 particles/m^2) when compared with other Arctic locations that use similar trawl methods (e.g., South of Svalbard: 0.34 ± SD 0.31 particles/m^3 (Lusher et al., 2015b), Kara Sea: 0.31–0.92 m^3, White Sea: 0.19–1 m^3 and eastern Barents Sea: 0.97–6.42 m^3 (Tosic et al., 2020); and Eurasian Arctic: 0.004 items m^3 (range of 0–2.4) (Yakushev et al., 2021)). Furthermore, our values are similar to those from a study performed in East Siberian and Beaufort Sea SW Greenland (0.026/particles/m^2) and in Tasiujarjuaq, Nunavut (0.014 particles m^2) (Liboiron et al., 2021). Caution is advised when comparing studies due to the lack of standardization in measuring meso- and microplastic concentrations. Harmonization of methods (e.g., GPS versus flowmeter, wind corrections) is essential for global data comparability (Pasquier et al., 2022). Additionally, white and green paint particles were excluded from our spatiotemporal distribution analysis, meaning actual M/MP concentrations may be underestimated.

Our methodology, including both sampling and laboratory protocols, was carefully designed. We utilized surface net sampling due to its proven effectiveness and operational reliability, (Tosic et al., 2020). By focusing on M/MP larger than 1 mm, we ensured suitability for citizen scientists and minimized contamination risks associated with smaller particles, leading to more accurate and reliable data. This methodological choice should be considered when comparing to studies that include particles <1 mm, as focusing solely on particles >1 mm may underestimate meso- and microplastic concentrations. This study represents an important initial step in evaluating sample variation within the target area, a key priority for determining the number of replicates needed to achieve sufficient statistical power and representativeness for the region (Fisner et al., 2017; Kershaw and Rochman, 2015; Korez et al., 2019).

4.8. Challenges and opportunities for citizen science in Arctic microplastic research

As demonstrated in this study, well-designed and properly supervised citizen science initiatives are highly effective for collecting microplastic samples in nearshore locations; however, subsequent analysis using spectrometric techniques is essential for accuracy. For instance, in our study, spectrometric analysis identified 54 particles (13 % of the total) as natural materials, highlighting potential misidentifications without such advanced verification.

Given the unique challenges of Arctic M/MP monitoring, we recommend integrating community-based data from citizen science into existing platforms and research databases. For example, the Local Environmental Network (LEO) collects reports on unusual environmental events from non-scientists, contributing to Arctic research (Mosites et al., 2018). *Fjord Phyto*, a NASA-funded citizen science initiative, gathers phytoplankton data in Antarctica via opportunistic platforms. Scientific research on plastic ingestion by northern fulmars (*Fulmarus glacialis*) involving public participation in helping to locate birds, has become a key tool for monitoring temporal and spatial pollution patterns (van Franeker et al., 2011). This approach is integrated into OSPAR (2015), and the Marine Strategy Framework Directive (EU, 2008), and is expanding into North Atlantic and Pacific environmental policies. Citizen science has proven to provide valuable regional data (De Sherbinin et al., 2021) and it was instrumental in assessing the variation of meso- and microplastics along the German coasts (Walther et al., 2024) and in establishing the first globally comparable baseline for microplastic pollution in the UK (Clark et al., 2023). Similarly, this approach could benefit Arctic research, helping to fill current knowledge gaps. Incorporating citizen science data into long-

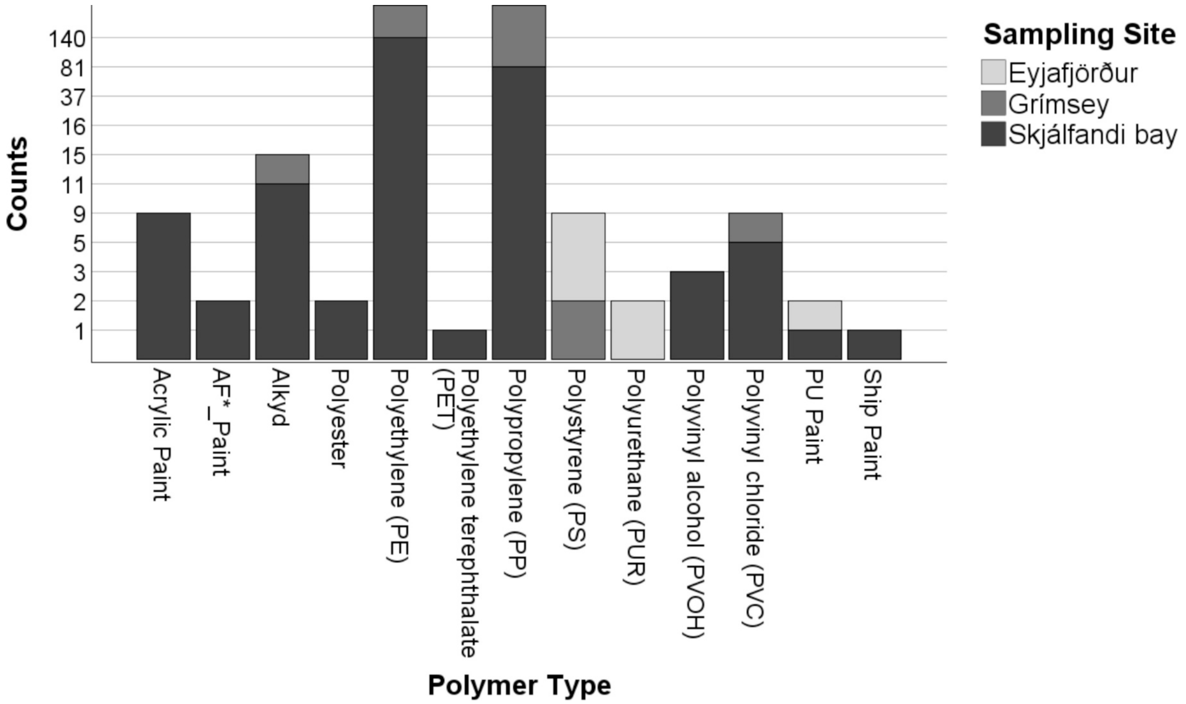

Fig. 9. Stacked bar chart showing the counts of different polymer types identified across three sampling sites: Eyjafjörður, Grímsey, and Skjálfandi bay. The data illustrate the prevalence of various synthetic materials, including polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and different paint types across sites.

term marine monitoring programs such as those conducted by NOAA (2011) and arctic ecosystem-based monitoring programs such as those at CAFF (2017) could help overcome challenges related to limited sample sizes, particularly in difficult-to-access areas. Tourism platforms, such as whale-watching vessels, provide a practical platform for systematic M/MP sampling, particularly with surface trawls, which operate at the cruising speed of vessels. Integrating microplastic research with ongoing opportunistic cetacean observation studies could provide valuable insights into whale interactions with marine debris, thereby enhancing both marine plastic pollution and whale research. For example, a recent master's study examined M/MP concentrations in Skjálfandi bay and their potential ingestion by baleen whales using data collected through the same citizen science program (Young, 2023).

The frequent challenges of citizen science integration into scientific research include limited contributor expertise (Foster-Smith and Evans, 2003), inconsistent methods, and irregular volunteer participation (Galloway et al., 2006), which can result in data gaps and skepticism about data quality (Delaney et al., 2007). Consequently, personnel training and standardized protocols are essential preconditions to strengthen the credibility and effectiveness of citizen science in meso- and microplastic research. Additionally, technological tools are increasingly being developed to validate citizen science data. Adopting customized technological frameworks with integrated quality metrics—such as validation through scientific consultation or visualization tools—can significantly enhance data reliability. For instance, software such as that used in the CoralWatch Project (Alabri and Hunter, 2010) could be customized to help detect and validate microplastic particles, thereby improving the effectiveness of citizen science in research.

Our recommendations are built upon systematic citizen science initiatives previously undertaken to monitor plastic pollution in seas, rivers, and coastal areas. Notable examples include the *Plastic Pirates* project, an EU-funded initiative that engages schools and youth across Europe in collecting data on macro and microplastics found in and around rivers and seas, and *Marine Litter Watch*, a citizen-based app and an online platform designed to address data gaps in beach litter monitoring, as required by the Marine Strategy Framework Directive.

Overall, meso- and microplastic pollution in Northeast Iceland's fragile marine ecosystems may disrupt trophic interactions, reduce biodiversity, and pose risks to marine species (e.g., krill, fish, and whales). These effects can propagate through the food web via bioaccumulation in marine organisms and ultimately impact human health through seafood consumption.

5. Conclusions

Fishing gear–especially lines made of polyethylene and polypropylene–dominates marine plastic pollution in Icelandic waters, posing a significant environmental threat to marine life, from large filter feeders to microscopic organisms. The high primary productivity of Northeast Iceland, fueled by nutrient-rich waters, suggests that zooplankton are likely to ingest M/MP, potentially introducing it into the food web and affecting larger species like whales.

Well-structured and robust community-driven monitoring projects that involve collaboration between research institutions, commercial partners, tourism companies, and non-profit organizations are critical for long-term success, enabling communities to collect important systematic data on the abundance and distribution of M/MP pollution, monitor marine species, and report on ecosystem changes.

Based on our experience, we recommend similar community-based citizen science programs to complement existing M/MP research and monitor pollution trends. This approach can help inform government policies to protect critical biodiversity areas and establish marine protected areas (MPAs). A multi-matrix monitoring approach, as seen in the Pan-Arctic region, is consistent with best practices and demonstrates the potential of citizen science for effective M/MP monitoring programs. This approach provides crucial data to local stakeholders and policymakers to support the development of marine conservation strategies and the fight against plastic pollution. These efforts are in line with the UN Sustainable Development Goals (SDGs) and Iceland's 2030 Agenda for Sustainable Development (UN, 2023).

Ultimately, given the ecological importance of Northeast Iceland and the threats posed by M/MP, community-driven initiatives are key to

Table 4
Comparison of the results obtained in this study to previous studies on meso- and microplastics (M/MP) abundance in the Arctic. * NE: Northeast. Ref: Reference.

Study area	x = M/MP/m^3 ± SD (min-max)	$\bar{x}$ = M/MP/km^2 ± SD (min-max)* 10^{-3}	$\bar{x}$ = M/MP/m^2 ± SD/m^2	Sample size	*Ref.
*NE Iceland Hope Spot	0.02 ± SD 0.03 (0–0.23)	6 ± SD 5.1 (0–38)	0.005 ± SD 0.006	58	Present study
South Svalbard	0.34 ± SD 0.31 (0–1.31)			21	(Lusher et al., 2015b)
Kara Sea	(0.31–0.92)	(16–50)		3	(Tosic et al., 2020)
White Sea	(0.19–1)	(34–84)		5	(Tosic et al., 2020)
Barent Sea	(0.97–6.42)	(74–1155)		3	(Tosic et al., 2020)
Eurasian Arctic	0.004 (0–2.4)			48	(Yakushev et al., 2021)
East Siberia	0.01	2		18	(Yakushev et al., 2021)
Lavtep Sea	0.002	0.4		20	(Yakushev et al., 2021)
Greenland SW			0.026 ± SD 0.026	8	(Liboiron et al., 2021)
Nunavut			0.014 ± SD 0.008	4	(Liboiron et al., 2021)
Beaufort Sea		7.5 ± SD 7.6 (0.9–28)		10	(Ikenoue et al., 2023)
Baltic Sea	0.2 ± 0.2 (0.3–2.1)			12	(Setälä et al., 2022)
Chukchi Sea	0.23 ± 0.07 (0.086–0.31)			6	(Mu et al., 2019)

advancing research, enhancing conservation, and ensuring the protection of vulnerable marine ecosystems.

CRediT authorship contribution statement

Belén G. Ovide: Writing – review & editing, Writing – original draft, Resources, Methodology, Data curation, Conceptualization, Formal analysis, Project administration. **Eleonora Barbaccia:** Writing – original draft, Writing – review & editing, Data curation, Conceptualization, Software, Formal analysis, Visualization. **Claudia Lorenz:** Validation, Software, Formal analysis, Data curation. **Charla J. Basran:** Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization. **Erica Cirino:** Writing – original draft, Methodology. **Kristian Syberg:** Validation, Supervision, Investigation, Conceptualization. **Marianne H. Rasmussen:** Validation, Project administration, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Belén García Ovide reports equipment, drugs, or supplies was provided by North Sailing. Belén García Ovide reports administrative support was provided by Ocean Missions. Belén García Ovide reports equipment, drugs, or supplies was provided by BioPol ehf., Marine Biotechnology Science Hotel. If there are other authors, they 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.2025.117638.

Data availability

Data will be made available on request.

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