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# Assessing Seafloor Litter Classification: Lessons from an Online Proficiency Test

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## Abstract
Seafloor litter is an applied indicator for the assessment of marine pollution. Harmonized seafloor litter categorization is essential for quality assured assessments. This study aimed to assess the quality of seafloor litter classification and the effectiveness of the International Council for Exploration of the Sea (ICES) seafloor litter categorization guidelines through an online proficiency test. Participants classified pictures of seafloor litter from trawls based on the ICES manual and photo guide. The test identified correlations between users' experience and classification accuracy. Findings demonstrated participants had a good ability to classify seafloor litter items based on the guidelines with an average accuracy rate of 83%. Some items were misclassified, but these errors could not be linked to the experience of the participants. Misclassifications during the proficiency test could be related to the nature of the picture-based assessment, a lack of participant knowledge of seafloor litter, and/or a lack of clarity in classification guidelines. The results of the test can be used as part of quality assurance measures to strengthen monitoring guidelines, future data collection and improve our understanding of potential human error in seafloor litter datasets.

**Keywords** Seafloor litter · Monitoring · Marine environment · Proficiency test · Quality control · Plastic pollution

## Highlights
- Participants show an 83% accuracy rate in categorizing seafloor litter items.
- Misclassifications may stem from the picture-based assessment, limited participant knowledge, or unclear classification guidelines.
- The proficiency test provides quality assurance for monitoring guidelines.

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## Introduction

Large quantities of litter enter the world's ocean each year, primarily as solid waste like plastic, and to a lesser extent metal, rubber, and glass (Jambeck et al. 2015; Geyer et al. 2017; Morales-Caselles et al. 2021). Much of this litter is land-based and is transported to the marine environment through rivers (Meijer et al. 2021; Harris et al. 2021b; Nyberg et al. 2023), while a smaller proportion enters via direct emission from coastal zones (Lebreton et al. 2017). It can also enter directly from sea-based activities such as fisheries, mariculture and shipping (Lechthaler et al. 2020; Lebreton et al. 2022; Kammann et al. 2023). Once in the marine environment, litter disperses quickly via wind, waves, and currents (Van Sebille et al. 2020). It can wash onto coastlines (Olivelli et al. 2020), or sink to the seafloor (Harris et al. 2021b; Int-Veen et al. 2021; Galgani et al. 2022; Harris et al. 2023; Kaandorp et al. 2023). Harmful impacts of seafloor litter, such as entanglement, ingestion, and smothering, have been documented for hundreds of marine species, resulting in injury, reduced mobility, and increased mortality (Kühn et al. 2015; Werner et al. 2016; Santos et al. 2021). The impacts on benthic habitats are less well known, but evidence suggests seafloor litter can serve as artificial substrates for settling invertebrates, as well as abrade or smother natural substrates, altering their complexity and ecosystem functioning (Green et al. 2015; Enrichetti et al. 2021; Ladewig et al. 2024). Despite these known negative impacts, questions remain regarding the movement, behavior, and sources of seafloor litter across spatial and temporal scales (Madricardo et al. 2020; Canals et al. 2021; Barry et al. 2023), information that is important for informing future mitigation measures to reduce marine litter.

Effective measures to address the problem of seafloor litter depend on the availability of reliable data. Data on seafloor litter can be collected as bycatch in trawls (Maes et al. 2018; Barry et al. 2022; ICES 2022a), or through in-situ measurement systems such as sonar, spectral imaging, capacitance, and optical sensing systems (Sandra et al. 2025). Recent advances in artificial intelligence and machine learning are also increasingly being explored to automatically detect and classify marine litter imagery collected by such systems (AI) (Politikos et al. 2023; Sandra et al. 2025). To date, numerous studies across broad spatial and temporal scales and significant water depths have documented seafloor litter (Galgani et al. 2000; Keller et al. 2010; Ramirez-Llodra et al. 2013; Pham et al. 2014; Woodall et al. 2015; Maes et al. 2018; Zablotski and Kraak 2019; Pierdomenico et al. 2019; Ryan et al. 2020; Vanavermaete et al. 2023). These data reveal that benthic litter is unevenly distributed, and influenced by both natural and anthropogenic factors related to sources, transport, and deposition mechanisms. While recent model-based predictions of seafloor litter densities show potential in identifying hotspots, multiple issues, such as variability in data collection methods and biases in geographical sampling, can hinder comprehensive analyses and trend detection (Maes et al. 2018; Haarr et al. 2022; Harris et al. 2023), and field validation continues to be needed. Thus, long-term monitoring of seafloor environments, using quantitative approaches conducted in a coordinated and holistic manner across various depths and habitats (Canals et al. 2021), can provide a more comprehensive understanding of litter dynamics and impacts and guide policy interventions and decision making. For example, these approaches can be used to identify hotspot areas in need of remediation, better inform risk assessments by determining the different types and levels of seafloor litter that could harm marine species and habitats, provide knowledge of different litter types to assess strategies for targeted litter reduction policies or in situ removal activities, and improving trend detection for measuring the effectiveness of litter reduction policies (GESAMP 2019; Canals et al. 2021).

In Europe, frameworks for litter monitoring are provided by the Marine Strategy Framework Directive (MSFD) and four regional sea conventions: The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR), Baltic Marine Environment Protection Commission, Black Sea Commission, and United Nations Environment Program/ Mediterranean Action Plan (UNEP/MAP) Barcelona convention for the Mediterranean Sea. For monitoring seafloor litter, these programs primarily rely on trawl surveys conducted for fish stock assessments, which poses specific challenges due to the reliance on opportunistic and synergistic data acquisition (Galgani et al. 2024): trawls do not provide precise information on the spatial distribution of litter on the seafloor nor sample over rocky bottoms (Madricardo et al. 2020; Sandra et al. 2025); variations in trawling methods and equipment across regions complicate data consistency; and may underestimate the abundance of small litter that pass through the trawl mesh (Moriarty et al. 2016; GESAMP 2019; Barry et al. 2022). Local or national standardization, like the Mediterranean International Trawl Survey (MEDITS) program, has been somewhat successful, but broader uniformity is challenging due to differing substrates and fish stocks (Cau et al. 2024). Despite these shortcomings, the use of benthic trawl surveys remains a practical and cost-effective way to monitor seafloor litter over large areas and long periods (e.g., Maes et al. 2018; Zablotski and Kraak, 2019).

To achieve more informed assessments of seafloor litter, it is essential to first correctly classify seafloor litter. Implementing a standardized approach to the identification and classification of seafloor litter is critical for source identification and detecting change over time, which directly leads to the development of preventative strategies and the ability to measure the effectiveness of subsequent policy interventions (Moriarty et al. 2016; GESAMP 2019; Canals et al. 2021; Barry et al. 2023). Adequate categorization of litter items requires balancing the practical tracing of an item to its source by minimizing the number of categories to reduce complexity and save time for field surveyors, while ideally being compatible with other classification schemes (Hapich et al. 2022). Litter criteria need to be comparable among monitoring programs to understand the movement of litter between environmental compartments. Further, harmonized guidelines facilitate the integration of data from various sources, creating comprehensive datasets that are more robust and valuable for scientific analysis and policymaking. Finally, quality assurance is essential for the effectiveness of monitoring programs, ensuring the accuracy and reliability of collected data. To date, litter categorization systems have been typically defined based on the array of items commonly found in the monitored regions and designed with specific management questions in mind, such as item-to-source attribution, identifying pathways of waste and items of concern for marine wildlife, or involving stakeholders in supporting preventative measures (Viega et al. 2016; Falk-Andersson, 2021a; Galgani et al. 2024). Intercomparison exercises between seafloor litter assessors are lacking, potentially leading to unidentified differences and issues in seafloor litter categorization. For example, in assessments of litter data collected by citizen scientists, variations in observer skills or focus have been found to result in the unintentional misclassification of litter items, particularly for rare or hard to distinguish items, which can hamper source identification, lead to systematic undercounts, and hide true environmental change (Merlino et al. 2021; Corbau et al. 2025). These issues may also apply to seafloor litter surveys, since they are conducted alongside fish stock assessments, and these conditions (including time restrictions) often prevent a comprehensive examination of all litter items.

The International Council for Exploration of the Sea (ICES) is an intergovernmental marine science organization established in 1902 that coordinates research and provides advice on the sustainable use of oceans, specifically in the North Atlantic. This coordination is delivered through Working Groups (WGs), with members consisting of National representatives and scientific experts from across the region, and is managed by thematic Steering Groups (SGs). ICES steers the harmonization of trawl surveys covering the European continental shelf from the Shetland Islands to the strait of Gibraltar, including the Baltic Sea, Skagerrak, Kattegat, North Sea, English Channel, Celtic Sea, Irish Sea, and Bay of Biscay (ICES 2017). Information collected through these surveys is entered into the ICES Database of Trawl Samples (DATRAS), providing quality-assured, standardized, publicly available raw data and data products (ICES 2023). In 2011, ICES began recording seafloor litter in benthic trawl surveys and later in 2018 established the ICES Working Group for Marine Litter (ICES WGML) within the Human Activities, Pressures, and Impacts Steering Group (HAPISG). Experts in the ICES WGML developed a guidance document, or manual, for the counting, weighing, measuring and categorization of collected litter (ICES 2022a) from trawl surveys, as well as an accompanying photo guide that depicts examples of seafloor litter items from all major categories (ICES 2022b). These guidelines were designed to accommodate seafloor litter monitoring as a secondary objective to fish stock assessments, while being practical and user-friendly on board ships, enabling efficient categorization with minimal effort. Further, the ICES manual allows for standardized monitoring, reducing differences in the collection, classification, and reporting procedures across participating nations, thus increasing data comparability and allowing assessments of specific litter items across broad spatial and temporal scales. However, to date their accuracy in categorizing seafloor litter collected from the North-east Atlantic has not been evaluated, preventing a broader understanding of their effectiveness in harmonizing seafloor litter data collection and reporting, and ultimately their usefulness for trend detection and policy applications.

In this study, we evaluated the usability and practical application of the ICES manual for seafloor litter data collection and reporting (ICES 2022a, b) using an online proficiency test designed to measure the accuracy of individual participants involved in seafloor litter monitoring (e.g., surveyors, researchers, etc.) in classifying seafloor litter items recovered from trawls. Notably, we aimed to assess if the occurrence of mislabeling litter items stems from a lack of comprehensive knowledge about the existing guideline or if it is caused by the lack of clarity of the guidelines. We hypothesized that participants' years of experience positively correlated with categorization accuracy. Furthermore, the results of the proficiency test were compared with the top ten list of seafloor litter items found in the European Sea from Barry et al. (2023) to investigate if the frequency of specific items collected from the seafloor would affect participants' categorization accuracy. The proficiency test holds significant importance as it: (a) tests the accuracy and effectiveness of seafloor litter data collection; and (b) operates to evaluate the quality of the guidelines and verify any prevalent issues. To our knowledge, such quality assurance and quality control mechanisms have not been employed for the analysis of seafloor litter reporting; the outcome of this study will therefore be invaluable in advancing seafloor litter categorization methodologies for both current and future assessments.

# Methods

## Survey Approach

The proficiency test was designed to assess participant's ability to correctly categorize seafloor litter and to evaluate the efficiency of the ICES seafloor litter guidelines. The test was conducted using the web-based tool mentimeter.com, which provided a user-friendly platform for the assessment. The test included a section where participants provided associated data on their profile, such as years of experience in marine litter observation, the average number of trawls conducted annually in field, country of data collection, affiliated organizations or vessels, and the marine litter surveys they engage in.

The test featured 38 images depicting seafloor litter items, each with five predefined categorical options derived from the ICES manual, including "Not litter" and "Unsure" (Supplementary material Table S1). Participants were required to select what they believed to be the appropriate category for each litter item displayed based on the ICES guidelines. One of the categories would be set as the correct answer according to the definitions in the guidelines.

The seafloor litter images were sourced from the Centre for Environment and Aquaculture Sciences (Cefas), and the Institute of Marine Research at the Swedish University of Agricultural Sciences (SLU). All images were taken of seafloor litter items collected by benthic trawls during ICES-coordinated fish stock assessment monitoring. This ensured the use of pictures of authentic and representative litter items for the proficiency test assessment. The images provided were collected between 2020 and 2021, with a range of demersal bottom trawl types depending on the specific survey, including 4 m beam trawls and grande ouverture verticale (GOVs) trawls. The proficiency test was accessible from December 2022 through August 2023 and disseminated through the ICES working group chairs forum and through specific emails to ICES expert groups linked to (1) fisheries surveys and (2) pollution monitoring: International Bottom Trawl Survey Working Group (IBTSWG), Baltic International Fish Survey Working Group (WGBIFS), Working Group on Beam Trawl Surveys (WGBEAM), Working Group on Nephrops Surveys (WGNEPS), Working Group on Introductions and Transfers of Marine Organisms (WGITMO), Marine Chemistry Working Group (MCWG), Working Group on Biological Effects of Contaminants (WGBEC). The objective was to identify the accuracy among individuals directly involved in marine litter monitoring, the effectiveness of the ICES guidelines among the most likely users, and the gaps in knowledge or areas where users may struggle with categorization.

## Participants

We obtained responses from a total of 70 participants mostly from Europe, but also from Canada, Ghana, and the United States of America. Less than 50% of the respondents were from English speaking countries. All participants were affiliated with marine research institutions or marine academic research groups, with the majority having participated in marine litter surveys ($N = 49$).

Ethical approval was secured for the study. Participants were informed on the study's objectives, procedures, and data application. Their involvement was voluntary, and measures were taken to ensure anonymity.

## Data Analysis

The percentage of correct answers was computed for each item by dividing the number of correct answers by the total number of participants. The overall categorization accuracy of participants, as well as for each litter item presented, was computed using mean and standard error (Mean ± SE). Descriptive statistics, such as the years of experience and number of trawls per year, were applied to enable the characterization of the study's participants. For comparison with the top ten items by Barry et al. (2023), the combined list including three European regions, the Great North Sea (GNS), Celtic Sea (CS) and Bay of Biscay (BB), was used (Table 1). This list was created based on the data generated by the coordinated national and regional seafloor litter monitoring programs collecting marine litter data between 2012 and 2020, and which was submitted to the ICES Data Centre, DATRAS.

A one-way ANOVA was conducted to assess significant differences in classification accuracy among participants with varying years of experience. Participants were divided into five experience groups: "None," "0-1 year," "1-2 years," "2-5 years," and ">5 years." Before performing the ANOVA, assumptions of normality and homogeneity of variance were checked using the Shapiro-Wilk test ($W = 0.97$, $p = 0.08$) and Levene's test ($F\ (4, 67) = 0.44$, $p = 0.78$), respectively. For items where classification accuracy was below the overall mean ($< 83\%$), a pairwise Fisher's Exact Test was used to account for small binomial sample sizes and to examine differences between experience groups (Supplementary material Table S2 and S3). Where significant differences were identified, answer counts were examined to determine which group outperformed the others. All statistical analyses were performed using R (version 4.2.3; R Core Team, 2024) and R Studio (version 2023.06.1).

**Table 1** Seafloor litter items with a mean classification accuracy below the average level of 83%

| Item | Image | Item category | Participants classification | *N* | Classification accuracy (%) | GNS + CS + BB (Barry et al., 2023) |
|---|---|---|---|---|---|---|
| 2 |  | F2 Shoes | F2 Shoes | 53 | 76 | - |
| | | | F1 Clothing/rags | 7 | | |
| | | | F3 Other | 7 | | |
| | | | C1 Rubber boots | 3 | | |
| 3 |  | A7 Synthetic rope | A7 Synthetic rope | 57 | 81 | 1 (25.1%) |
| | | | E2 Rope (natural fibers) | 12 | | |
| | | | A8 Plastic fishing net | 1 | | |
| 5 |  | A11 Plastic crates and containers | A11 Plastic crates and containers | 57 | 81 | - |
| | | | A14 Other plastic | 9 | | |
| | | | A2 Plastic sheet | 2 | | |
| | | | A3 Plastic bag | 2 | | |
| 6 |  | E1 Wood (processed) | E1 Wood (processed) | 52 | 74 | - |
| | | | Unsure | 9 | | |
| | | | A14 Other plastic | 5 | | |
| | | | Not litter | 2 | | |
| | | | C3 Bobbins (fishing) | 1 | | |
| | | | NA | 1 | | |
| 9 |  | A14 Other plastics | A14 Other plastic | 39 | 56 | 6 (8.9%) |
| | | | B5 Metal appliances | 27 | | |
| | | | Unsure | 3 | | |
| | | | Not litter | 1 | | |
| 12 |  | A7 Synthetic rope | A7 Synthetic rope | 43 | 61 | 1 (25.1%) |
| | | | E2 Rope (natural fibers) | 23 | | |
| | | | Unsure | 3 | | |
| | | | A8 Plastic fishing net | 1 | | |
| 13 |  | A8 Plastic fishing net | A8 Plastic fishing net | 46 | 66 | 7 (5.9%) |
| | | | A7 Synthetic rope | 18 | | |
| | | | A6 Monofilament (entangled) | 4 | | |
| | | | A16 Other fishing related plastics | 1 | | |
| | | | Not litter | 1 | | |
| 24 |  | A16 Other fishing related plastic | A16 Other fishing related plastic | 52 | 74 | 2 (22.3%) |
| | | | B3 Fishing related metal | 12 | | |
| | | | A8 Plastic fishing net | 6 | | |

**Table 1** (continued)

| Item | Image | Item category | Participants classification | *N* | Classification accuracy (%) | GNS + CS + BB (Barry et al., 2023) |
|---|---|---|---|---|---|---|
| 26 |  | A14 Other plastics | A14 Other plastic | 57 | 81 | 6 (8.9%) |
| | | | C3 Bobbins (fishing) | 7 | | |
| | | | Unsure | 4 | | |
| | | | B3 Fishing related metal | 2 | | |
| 28 |  | A3 Plastic bag | A3 Plastic bag | 56 | 80 | 4 (12.7%) |
| | | | A2 Plastic sheet | 8 | | |
| | | | A11 Plastic crates and containers | 3 | | |
| | | | A14 Other plastic | 2 | | |
| | | | Unsure | 1 | | |
| 29 |  | A6 Monofilament (entangled) | A6 Monofilament (entangled) | 56 | 80 | 5 (9.6%) |
| | | | A5 Plastic cable ties | 13 | | |
| | | | A8 Plastic fishing net | 1 | | |
| 31 |  | C3 Bobbins (fishing) | C3 Bobbins (fishing) | 46 | 66 | - |
| | | | C6 Other rubber | 17 | | |
| | | | C4 Rubber tire | 3 | | |
| | | | A16 Other fishing related plastic | 2 | | |
| | | | Unsure | 2 | | |
| 32 |  | E2 Rope (natural fibers) | E2 Rope (natural fibers) | 48 | 69 | 8 (3.7%) |
| | | | A7 Synthetic rope | 21 | | |
| | | | A5 Monofilament | 1 | | |
| 35 |  | D4 Other glass/ ceramics | D4 Other glass/ ceramics | 34 | 49 | - |
| | | | D3 Ceramic piece | 22 | | |
| | | | E5 Other natural product | 7 | | |
| | | | Unsure | 5 | | |
| | | | Not litter | 2 | | |
| 37 |  | E1 Wood (processed) | A16 Other fishing related plastic | 26 | 27 | - |
| | | | E1 Wood (processed) | 19 | | |
| | | | A6 Monofilament (entangled) | 14 | | |
| | | | Unsure | 7 | | |
| | | | B3 Fishing related metal | 4 | | |

For each question, the various categories chosen by participants for each item are listed, along with the count of participants who selected each respective category and percent of correct classification. The frequency of seafloor litter items in European waters (GNS, CS and BB) are included with the number representing placement in the top ten list as well as frequency of occurrence (percentage) derived from Barry et al., (2023). *GNS* Great North Sea, *CS* Celtic Sea, *BB* Bay of Biscay

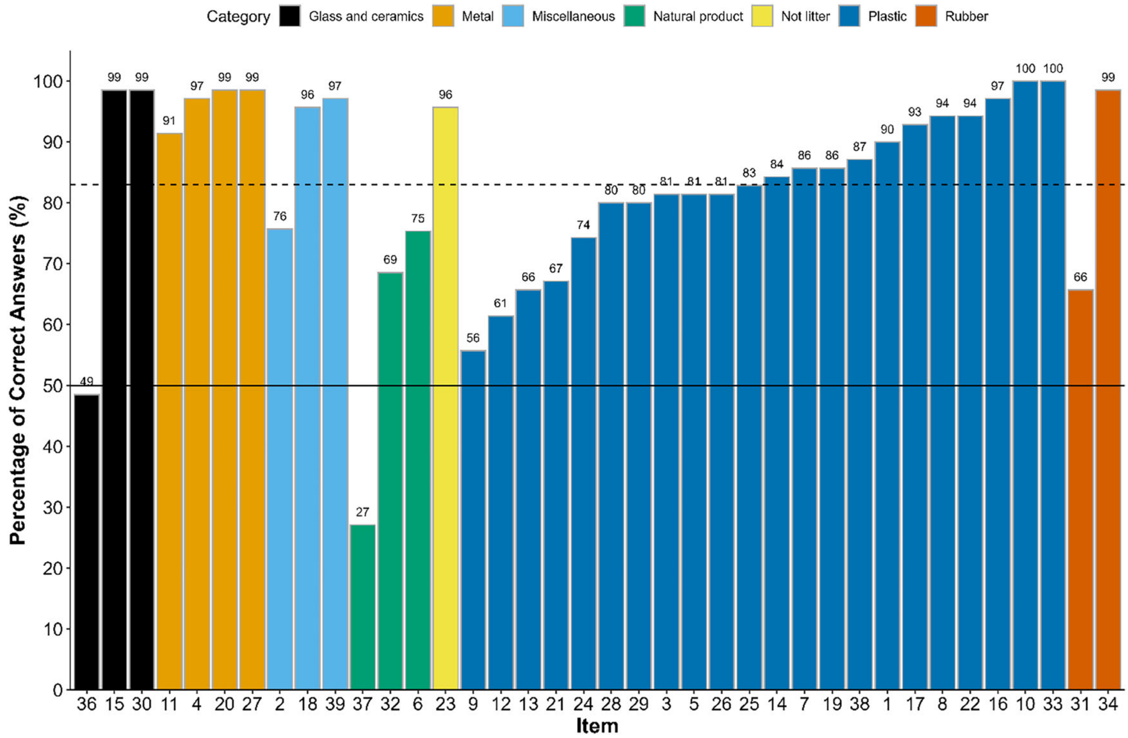


**Fig. 1** The percentage of correct answers per question. Item number refers to the order of seafloor litter images presented in the online proficiency test (see Table 1 and Supplementary material Table S1). Solid line represents the 50%-mark, dotted line represents the mean of correct answers of 83%. Material categories are represented by color. Exact values for each item are given above bars

## Results

The proficiency test results indicated that the participants demonstrated a good ability to categorize seafloor litter items across the test, with an average accuracy rate of 83 ± 2%. Participants were able to accurately classify >95% for 12 items from 6 different material categories (Fig. 1), with the best identified being A15 Medical mask and A3 Plastic bag (100%), followed by D2 Glass bottles, B1 Food can, B2 Beverage can, D1 Glass jar, and C5 Rubber glove (99%). Despite this overall high accuracy, several items were considered as misclassified, resulting in scores as low as 27% for individual items (Fig. 1). Items in the category Natural materials showed the lowest classification accuracy, whereas approximately 50% of the plastic items presented were classified correctly at rates above the overall mean.

Table 1 presents the litter items that exhibited a categorization accuracy below the study’s average of 83% as well as insights into the prevalence of these categories in European waters. Many less-accurately classified items aligned with those identified by Barry et al. (2023) as among the top 10 most frequently encountered seafloor litter items in European Seas. For instance, while A7 Synthetic rope was reported as the most frequently encountered seafloor litter item by Barry et al. (2023), participants correctly classified this type of item with a 61% or 81% accuracy (Table 1). Overall, Table 1 includes all predominant plastic items that occupy the top five positions in the GNS, CS and BB region, such as synthetic rope, plastic sheet, monofilament (entangled), and plastic bag.

Among the 70 respondents, 14% of participants had no prior experience, 12% had 0-1 years of experience, 11% had 1-2 years of experience, 29% had 2-5 years of experience, and 33% had >5 years of experience. In general, there was no statistically significant difference in the accuracy of seafloor litter categorization between the five groups of experience ($F(4, 65) = 0.676$, $p = 0.61$). Further analysis on items classified below the average revealed a statistically significant difference between experience groups only for item 21, A2 Plastic sheet. A following pairwise comparison revealed a significant difference between the “2-5 years” and “>5 years” groups ($p = 0.003$), were the “2-5 years” group performed better.

## Discussion

The results of the proficiency test offer valuable insights for enhancing quality assurance measures in future data collection and for preventing human errors in databases such as DATRAS. Overall, participants demonstrated a good ability to classify seafloor litter items, with an average accuracy of

83%. No significant differences in classification accuracy were observed between experienced and less-experienced participants. These findings support the effectiveness of the ICES manual as a reliable guideline for categorizing seafloor litter recovered from trawl surveys.

## (Mis)Classification of Seafloor Litter in Picture-based Assessments

Despite the overall high accuracy rate, several items were misclassified by participants, regardless of their experience with seafloor litter collection. Three main factors may have contributed to these misclassifications during the proficiency test: (1) the inability to physically handle the items, (2) unfamiliarity with certain objects or lack of expert knowledge of objects not previously encountered in real life, and (3) unclear category descriptions or ambiguous category definitions in the provided guidelines.

The misclassification by participants of varying experience levels highlights a potential limitation of using an image-based assessment in place of real-time categorization. For example, item 32 (a degraded or fouled rope) and item 37 (a wooden fishing gear component containing plastic elements), as well as other mixed-material items, were more frequently misclassified. Seafloor litter, often subjected to prolonged weathering in the marine environment (Andrady 2015), can be difficult to identify. In a real-time setting, the ability to physically rotate an object, inspect for markings or brand names, and assess the weight and texture can significantly aid classification, especially when items no longer resemble their original form. This level of analysis is challenging with a single image, and the isolated nature of the proficiency test removed the collaborative environment typically found on research vessels, where group discussions may assist with categorization. In-practice categorization on board vessels, where items are handled directly, likely yields higher accuracy rates when using the ICES manual. However, the carefully selected images in this study suggest that the impact of not physically handling the items is somewhat mitigated. The image-based approach also offers a practical advantage by enabling widespread distribution to participants, facilitating broader assessments of categorization proficiency.

Picture analysis using cameras on ships, remotely operated vehicles (ROVs), or autonomous vehicles is increasingly employed to assess the occurrence and density of marine litter on the seafloor. A gradual switch towards video-based monitoring can therefore be expected due to technological advantages (Sandra et al. 2025) and potential future restrictions on bottom trawling given its destructive nature (UNEP, 2016). The use of video-imaging technologies is also recommended within the EU, as it enables improved assessment of interactions between litter and marine species (Galgani et al. 2023). However, the results of this study demonstrate that even under controlled conditions, image-based classification can lead to misclassification due to limited visual information and interpretation differences, highlighting challenges that are likely to be amplified in video-based monitoring. In such approaches, objects cannot be handled directly and may be partially buried in the sediment, further increasing identification uncertainty and often resulting in a higher proportion of unclassified items compared to trawl-based surveys. These findings highlight the need for categorization guidelines that are robust to image-based identification, including clearer definitions and improved visual references that are applicable across different monitoring methods. While standardization of marine litter categorization across methods (e.g., trawls, video, still images) cannot resolve limitations related to visibility or detection, it can improve consistency in how observed items are classified, thereby facilitating more comparable datasets (Nogueira et al. 2023). Artificial intelligence is also becoming more common practice and will likely play a key role in automated detection and classification of seafloor litter in the future, providing continuous and precise monitoring while potentially reducing observer bias compared to human classification. However, its performance depends on the quality and representativeness of training data and may still be affected by the same visual limitations identified in this study, particularly for fragmented items, where detection accuracy decreases as objects become smaller or lose distinguishing features (Sandra et al. 2025).

Participants unfamiliar with certain items in the test could have resulted in lower classification accuracy, which could explain observed differences. In addition, limited knowledge of fisheries equipment may influence results, as items such as net cuttings could be incorrectly classified if participants do not recognize them as fisheries-related materials. Conversely, greater familiarity with fisheries equipment may also affect classification, as participants could preferentially assign items to fisheries-related categories based on their prior knowledge, even when the manual prescribes a different classification. The ICES manual is designed for litter identification in the North-East Atlantic, and the test included images from this region. However, participants from other global regions also participated in the proficiency test. As the classification task was based on the standardized ICES categorization system and supported by a photo guide with clear images for each category, prior regional experience with seafloor litter monitoring was not expected to influence the ability to categorize items. The photo guide is intended to facilitate consistent identification and reduce misclassification due to unfamiliarity with specific litter items.

One key objective of this proficiency test was to evaluate the usability of the ICES manual. Our results indicate that misclassifications were not random but frequently occurred with items commonly encountered in European Seas (Table 1) (Barry et al. 2023; Maes et al. 2018). This suggest that many errors likely stem from unclear category descriptions rather than participants' inability to recognize the litter items themselves. For instance, categories with lower-than-average correct classification rates, such as E1 (Processed wood) and A14 (Other plastics), were identified as priority areas for improvement (Table 1). These findings are significant because improving these categories can directly enhance the accuracy of seafloor litter datasets. Re-running the proficiency test after these revisions can then assess whether the changes improve the manual's usability and classification accuracy.

## Improving Seafloor Litter Classification

To accommodate seafloor litter monitoring as a secondary objective to fish stock assessments, the ICES seafloor litter guidelines (ICES 2022a) were designed to be practical and user-friendly on board of ships, enabling efficient classification with minimal effort. This includes following a concise list for item categorization, to ensure data collection is quick while still comprehensive and informative for assessments and policy drivers. The simplicity of the ICES guidelines becomes clear when compared to other litter categorization lists. While the ICES guidelines define 6 categories and 42 subcategories, the CEMP guidelines for beach litter (OSPAR commission 2020) includes 10 categories with over 100 subcategories, and the European Joint Research Centre's (JRC) joint list contains 9 categories and more than 150 subcategories (types) (Fleet et al. 2021). However, the use of a smaller number of subcategories results in the broad grouping of diverse items, which can hinder source identification and reduce the policy relevance of the findings for informing targeted mitigation measures. For example, the so-called 'SUP Directive', Directive (EU) 2019/904 (EU Commission 2019), aims to reduce the impact of single-use plastics (SUP) and fishing-related litter, such as Abandoned, Lost and Otherwise Discarded Fishing Gear (ALDFG). Yet, the ICES guidelines group items such as reusable storage boxes, single-use food containers, and fish boxes from fisheries under the broad category "Crates and containers" (ICES 2022a). As only some of these items fall under SUP or fisheries-related waste, this broad categorization may complicate the evaluation of policy directives to reduce litter items (Falk-Andersson et al. 2025), and additional confusion may be introduced by samplers during the data collection stage if they are less familiar with the nuances of the ICES category list. To enhance source identification and improve the monitoring of SUP and fisheries-related waste, one might want to revise current seafloor litter categorization systems. However, the effectiveness of these seafloor monitoring programs for reliable trend analysis is already constrained by high temporal and spatial variability in litter concentrations, with only significant reductions being measurable (Galgani et al. 2022). Further subdividing litter items into increasingly specific categories, for example, from total litter items, to total plastic items, to plastic bottles, to plastic drinking bottles <1 L, reduces the number of observations per subcategory. With the current sampling intensity, obtaining representative data for rarely encountered, highly specific categories is likely to be difficult. A potential solution to this trade-off is the use of hierarchical categorization systems, where items are recorded at a detailed level but can be aggregated into broader categories for analysis, as implemented in the JRC Joint List (Fleet et al. 2021).

The proficiency test developed to assess the ICES manual for seafloor litter categorization also aims to improve harmonization with other categorization systems. Within Europe, several contracting parties of the regional sea conventions OSPAR, HELCOM and the Barcelona convention use their fish stock assessments for seafloor litter monitoring (OSPAR 2023; HELCOM 2023), which has been adopted as a common indicator in their respective regional action plans. Within the MSFD (EU) 2008/56 (EU commission, 2008), harmonization is crucial for minimizing differences in the collection, classification and reporting procedures among EU Member States. The possibility of comparing data over large areas is, however, hampered by the use of various trawls and methods leading to different estimates of litter quantities. Nevertheless, harmonized categorization is still essential to improve comparability, e.g. for identifying top litter items, and facilitating environmental assessments at both regional and European levels (Galgani et al. 2023). This may aid in setting reduction targets, defining threshold values, and determining Good Environment Status, all of which rely on consistent and comparable quantitative data and assessments.

The results in this study also show that categorization applying the ICES list was not 100% consistent among individual participants for all litter categories, and that some of the categories within the ICES list need to be better described and common misclassifications ascribed to the correct category to ensure consistency. The definition of specific marine litter categories is decided by the inventor of the category and the category list. Unlike species descriptions, which are published, reviewed and debated, there are no peer reviewed research articles describing specific marine litter categories (Hapich et al. 2022). Instead, various manuals provide descriptions of categories for specific purposes. Different matrices (i.e. seafloor, beaches, floating debris) have distinct category lists, making the connectivity between indicators and the understanding of marine litter movement challenging. Moreover, defining marine litter items can be complex. For instance, plastic bags vary in shape and can break down and degrade into potentially unrecognizable fragments, necessitating clear category definitions (Falk-Andersson et al. 2021b). Questions arise on whether mesh bags qualify as bags or whether soft plastics food packages should be categorized as bags or sheets. Fragmented items add further complications. These factors must be addressed to clarify and standardize the categorization list. However, specificity of seafloor litter monitoring should be considered when revising. A stronger alignment with other litter categorization systems such as the JRC joint list (Fleet et al. 2021) is strongly recommended, but the number of subcategories should be limited to increase trend detection and ensure feasibility of seafloor litter registration within existing fisheries surveys and monitoring programs. While higher-resolution categorization can provide more detailed information on litter sources and environmental risks, collecting such detailed data is often constrained by the operational context of seafloor litter surveys. These surveys are conducted alongside fisheries stock assessments, where limited time is available for examining each item retrieved in trawls. Increasing the number of subcategories may therefore reduce feasibility and consistency in routine monitoring. Nevertheless, higher-resolution classification may be particularly valuable for specific high-risk items, such as fishing gear, where more detailed identification can support improved understanding of environmental impacts and source attribution (Gacutan et al. 2022). Importantly, increased harmonization with other existing lists should also consider compatibility with previous gathered data to allow statistically underpinned time trend assessments.

An optimized manual for seafloor litter in trawls may also have larger applicability; the information acquired from this study could form the basis of a picture database of rigorously evaluated and categorized seafloor litter items. Creating a web-based picture library of litter objects could harmonize how individuals and AI categorize objects and would increase accessibility of the guidelines for all users. In addition, to increase usability among participants of different backgrounds and experience levels, categorization lists could also be translated into multiple languages. Although current seafloor litter guidelines aim to provide clear descriptions for all subcategories, language differences may still lead to non-harmonized classification. For example, terms such as "caps", "lids", "crates" or "containers" may be interpreted differently by native and non-native English speakers. While the present study did not assess participants' native language and therefore cannot determine whether this influenced misclassification, providing translated categorization lists could further support consistent interpretation of category definitions.

### Limitations of the Proficiency Test

In addition to some limitations mentioned above, other issues were also present in this study. To keep the proficiency test user-friendly while targeting a high number of responses, there were some inadvertent drawbacks introduced as a result. We were unable to include an example of litter from every category in the ICES guidelines, due to the lack of availability of good quality images for each litter category and the need to have some common items represented more than once to create an accurate view on overall litter classification accuracy. Additionally, during the test, participants selected an answer from a multiple choice of seven options, rather than the full 42 ICES categories. Therefore, their answers had already been limited which potentially influenced the process. A future online available proficiency test to train people in litter categorization and assessments ideally will include all available categories. A test available in different languages could also have enhanced the reach and participation.

However, although the proficiency test has its acknowledged limitations, this study has allowed us to gain a better understanding of the potential accuracy of litter data within the ICES DATRAS database. By assessing the overall average participant accuracy, reported in this study as 83%, we can acknowledge the level of data accuracy expected in the wider dataset. Misclassifications were more frequent for natural items and objects composed of mixed or degraded materials, which may introduce some bias in the reported composition of seafloor litter. Such patterns could influence the interpretation of monitoring data used in environmental assessments and policy reporting, as they may lead to systematic under- or overrepresentation of specific litter types, potentially masking real environmental changes or biasing source attribution and trend analysis.

## Conclusions

To come to a better understanding of marine litter, it is essential to correctly classify and quantify litter within the different monitoring indicators (e.g., seafloor, beach, and floating litter). A primary objective of litter classification is to support source identification. Accurate and consistent classification therefore forms the basis for interpreting litter distributions, understanding movement between environmental compartments, and ultimately measure mitigation or changes over time. The results of this study show that participants were generally able to classify seafloor litter items correctly using the ICES guidelines. This indicate that the ICES seafloor litter categorization guidelines and photo guide provide a useful framework for harmonized classification. At the same time, the proficiency test revealed that misclassifications occur and may arise from several factors, including the interpretation of images, limited familiarity with specific litter types, and ambiguities in the classification categories.

Harmonized guidelines ensure that data collected from different regions and monitoring frameworks (e.g., ICES, OSPAR, and the JRC Joint List) are consistent and comparable. Guidelines such as the ICES seafloor litter categorization and reporting manual provide clear protocols that enhance the accuracy and reliability of the data collected. Harmonized methods streamline this monitoring process, increasing quality and making it more efficient. They also facilitate the integration of data from different monitoring approaches and regions, creating comprehensive datasets that are more robust and valuable for scientific analysis and policymaking. A key outcome of this study is that the applied proficiency test provides a practical tool to support harmonization by providing insights into the overall accuracy of seafloor litter classification and identifying areas where improvements to the current ICES guidelines may be needed. Moreover, such a proficiency test can serve as a training tool for personnel working with the ICES seafloor litter guidelines. A permanent test setup would allow for repeated training and provide a way to assess classification accuracy and confidence over time.

Litter indicators and criteria also need to be comparable to understand the movement of litter between environmental compartments. Harmonization of monitoring methods and categorization is increasingly being addressed through international policy frameworks, including the JRC Joint List, regional sea conventions, and related scientific initiatives, although full harmonization across compartments and methods is still ongoing. However, systematic quality control measures such as proficiency testing should also be implemented to ensure consistency and reliability across different indicator datasets. Ultimately, policymakers wish to use such indicators to measure the effectiveness of legislation changes and pollution prevention and mitigation. By understanding the potential level of inaccuracy within data classification, researchers and policymakers can better interpret monitoring results and distinguish between real environmental changes and variations related to data collection.

As a final note, the authors do not want to overstate the effectiveness of seafloor litter monitoring as a tool to track changes resulting from policy interventions, as it is not inherently suited for this purpose. The continued use of such marine monitoring often stems from the availability of research vessels, where funding needs drive the search for justifications to utilize them. Seafloor litter monitoring often produces variable data due to differences in sampling methods, gear types, and substrate conditions, which can limit the detection of subtle changes over time. While large-scale reductions in broad litter categories may be observable over longer timescales, more granular changes remain difficult to detect. These limitations highlight that improving data quality through harmonized classification alone is not sufficient, representative and consistent sampling strategies are also required to support robust trend analysis. In this context, emerging image-based monitoring approaches may offer a complementary and potentially less intrusive alternative to trawl-based surveys. Our findings demonstrate that improving classification accuracy and reducing misclassification in image-based data is essential for strengthening source identification and ensuring the reliability of such approaches in future monitoring frameworks.

## Data Availability

The data supporting the findings of this study are derived from the proficiency test and is available from the corresponding author upon reasonable request.

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## Compliance with ethical standards

**Conflict of Interest** The authors declare no competing interests.

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