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Marine litter as a vector for fouling species in Iceland

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ABSTRACT

Marine litter has become a significant environmental issue with increasing evidence of its impact on oceans and coastal areas across the planet. This study focuses on the distribution and composition of marine litter in three regions of Iceland - Southwest, Westfjords and Northeast - and on marine litter as a vector for fouling species. The results of this study show that plastic litter was the most abundant type of both fouled and non-fouled marine litter. The beach surveys showed that land-based sources, such as mismanaged waste, were the primary contributors to beach pollution. In contrast, most fouled litter, such as fishing gear, originated from sea-based sources. Over 79,000 individuals belonging to at least 92 species were found on fouled litter at the eight surveyed sites. The Southwest had the highest abundance and the most fouled litter collected. However, the Westfjords had the highest diversity and species evenness. The phyla of the fouling species found included Annelida, Arthropoda, Bryozoa, Chordata, Cnidaria and Mollusca. Cnidaria exhibited the highest fouling percentage in the Southwest and Northeast regions, whereas Annelida had the highest fouling percentage in the Westfjords. Statistically significant relationships were found between species richness and region, abundance and region, material type, and surface rugosity and thickness. These findings highlight how fouling species can be transported via marine litter and underscore the need to continue monitoring marine litter in Iceland and implement management strategies to reduce its impact on the marine and coastal environment.

Keywords: Plastic, Land-based sources, Management strategies, Beached litter, Monitoring, Fishing industry, Mismanaged waste

INTRODUCTION

Over the past 20 years, marine litter has stirred global concern as awareness of its dangers to wildlife and humanity has risen. However, its persistence in the marine environment remains (Derraik, 2002; Gregory, 2009). Marine litter is defined by the United Nations Environment Programme as any persistent, manufactured, or processed solid material that is discarded, disposed or abandoned in the marine coastal environment (UNEP, 2009). The severity of the marine litter issue is underscored by recent estimates, placing the global abundance at approximately 82–358 trillion plastic particles polluting the ocean, collectively weighing between 1.1 and 4.9 million tons (Eriksen et al., 2023). Furthermore, plastics dominate marine litter, making up from 60 to 95% of all marine litter in surface waters to deep-sea sediments (Aretoulaki et al., 2020). The continued accumulation of marine litter pollution in our environment usually originates from one of five categories: (1) the Fishing industry, including aquaculture; (2) Galley waste (non-operational waste from shipping,

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fisheries, and offshore activities); (3) Shipping, including offshore activities (operational waste); (4) Sanitary and medical waste (sewage related waste) and (5) Public littering (tourism and other recreational activities) (UNEP, 2009). These categories are further divided into sea- or land-based sources. Broadly, land-based pathways for litter consist of mismanaged waste travelling along wind and rivers to enter the marine environment (Derraik, 2002). Sea-based litter often originates from the fishing industry and is categorized as abandoned, lost, or otherwise discarded fishing gear (He and Suuronen, 2018). However, it is widely accepted in contemporary literature that 80% of marine litter results from mismanaged land-based waste (Mehlhart and Blepp, 2012; Meijer et al., 2021).

Due to the ubiquitous nature of marine litter, it is found floating in the water column, inside sea ice, across marine benthic environments, and washed ashore in remote and urban coastal areas (Eriksson et al., 2013; Galgani, 2015 Pham et al., 2014; Jambeck et al., 2015; Strand et al., 2015). Consequently, this omnipresence results in environmental threats which are materialized into four distinct groups: (1) Dangers of ingestion and entanglement of wildlife; (2) Source and vector for contaminants in marine waters; (3) Socio-economic impacts; and (4) Spreading of fouling species, including non-indigenous species (NIS) and pathogens (Strand et al., 2015), whereby fouling species, also known as biofouling organisms, include plants, animals, and microorganisms that naturally settle and grow on surfaces in aquatic environments, including rocks, vessels, buoys, offshore platforms, and marine litter (Gregory, 2009; Munk et al., 2009; Thiel and Gutow, 2005; Bressy and Lejars, 2014; Kiessling et al., 2015). Barnacles, bryozoans and hydrozoans are examples of biofouling organisms as they attach to and colonise various substrates (Thiel and Gutow, 2005; Kiessling et al., 2015). Attachment may occur by physical or biological means, such as physical adhesion or entanglement, and can transport fouling species from one location to another (Thiel and Gutow, 2005). As these species adhere to various surfaces, they can have negative economic and visual impacts, such as slowing vessels by increasing drag when attached to the hull and reducing the aesthetics of the surface to which they are attached (Munk et al., 2009; Bressy and Lejars, 2014). Additionally, flexible rope masses from fishing gear may aggregate the larval and juvenile stages of multiple marine organisms (Gregory, 2009). Although marine litter fails to develop diverse and rich communities such as those on Sargassum and other drifting seaweed, it may transport fouling species (Winston et al., 1997; Gregory, 2009).

Furthermore, the rafting potential of marine litter has now begun to gather attention. Rafting potential refers to the ability of fouling species to disperse over long distances by attaching to floating debris (Kiessling et al., 2015; Rech et al., 2016). Dispersal by rafting may result in the distribution and colonisation of fouling species in new areas and can contribute to the spread of NIS, thus being highlighted as a biodiversity risk (Derraik, 2002; Gregory, 2009; Hammer et al., 2012; Pham et al., 2014; Strand et al., 2015; Rech et al., 2016; Shabani et al., 2019). Considering this, the collection and assessment of marine litter along the Icelandic coast are still in their early stages, necessitating further baseline data to track the origin of marine litter and identify the transported fouling species. However, current guidelines lack specifications for documenting observations of fouling species on collected litter. This gap may arise from the scarcity of fouling species, their small size or discrete composition causing them to go unnoticed, or from fouling species lying outside the focus of surveys, which therefore ignore them (Gregory, 2009). Ultimately, this results in missed opportunities to gather baseline data for monitoring fouling species and a gap in knowledge regarding the movements of these species on marine litter. With globalisation, industrial productivity, and population growth, the production of marine litter is expected to increase despite advances in waste management. Consequently, this increase enhances the accumulation, movement, and potential dispersal of fouling species in Iceland via marine litter (Strand et al., 2015). This study investigates how beached marine litter serves as a vector for fouling species in Iceland, focusing on their distribution, composition, and ecological impact. Field surveys conducted at eight coastal sites across three regions involved the systematic collection and categorisation of marine litter and the recording and identification of fouling species. The study also compares species richness, abundance, material type, surface rugosity, and regional differences. Its ultimate goal seeks to document the diversity of marine litter and determine whether fouling species prefer specific materials.

METHODS

Field Sampling

Overall, eight sites were selected based on their location, accessibility, and presence of litter. Sampling occurred from August to November 2022; two sites were located in the Southwest (SW1: 64.03571; -22.71422 & SW2: 64.07772; -22.69504) in Sandgerði and Garður, three in the Westfjords (WFJ1: 66.07517; -23.12051, WFJ2: 66.06669; -23.12696, & WFJ3: 66.15056; -23.21578) in Ísafjörður and Bolungarvík and three in the Northeast of Iceland (NE2: 65.67705; -18.04695, NE3: 66.04037; -17.34302, & NE:4 66.05002; -17.36143) in Akureyri and Húsavík (Figure 1). Sampling closely followed the strategy outlined by Rech et al. (2018). Colonised litter items were collected from the entire shore area at each site (from the shoreline to the shore limit) and each item was inspected, identified, and photographed. Followed by the DeNIS protocol (the Marine debris & Non-Indigenous Species Protocol for Opportunistic Sampling) to categorise the collected marine litter (Canning-Clode et al., 2023). Following this protocol, the collected litter was categorised into material types (such as plastic, textile, and metal) and assigned a numbered code outlined by DeNIS. Surface rugosity (textured or smooth) and thickness (flexible or solid) of each litter item were recorded to provide further detail regarding the collected litter.

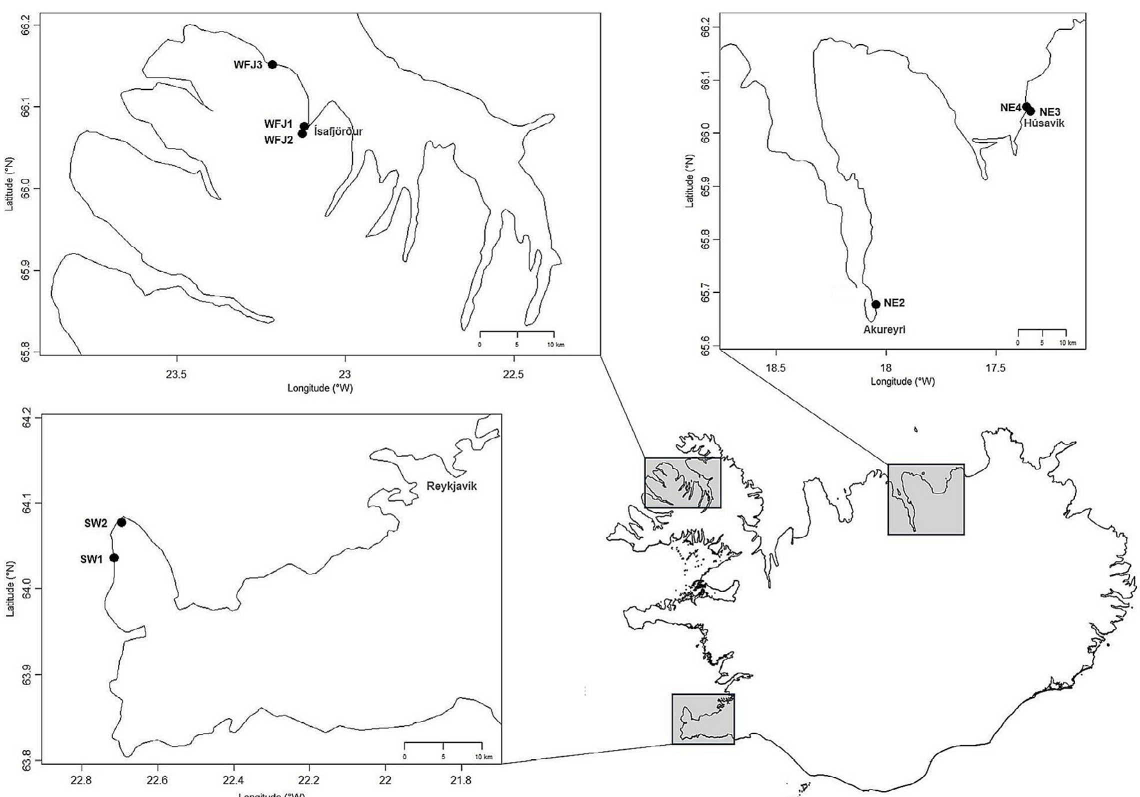

Figure 1. Map of sampling sites. SW – Southwest, WFJ – Westfjords, NE – Northeast.

Sampling took place immediately after the high tide to prevent the collected organisms from dehydrating and losing their morphological integrity due to air exposure. Each aforementioned site was sampled twice, and each sampling included two different types of surveys. The first type of survey consisted of collecting all fouled beached marine litter along the entire shoreline to determine if fouling species had material-related preferences. The second type of survey used standardised transects to count and classify fouled and non-fouled beached marine litter to record the diversity of the litter at each site. Beach characteristics such as the substrate composition on the upper and lower tidelines and surrounding industries were recorded to infer possible sources of the beached marine litter.

The aim of the first survey was to collect all fouled litter by a sampling process in which the entire area of each site was inspected for beached marine litter that visibly had attached fouling species to them. To determine the location and quantity of fouled litter items on the beach, the items were recorded in 10–meter wide segments along the shoreline (Figure 2). Once a piece of litter was found, it was given a short visual description in the field, placed into a bucket by hand, and subsequently transported back to the laboratory for further analysis at the end of field sampling. In case of large litter items, sections that were visibly fouled were cut off and placed in a bucket for laboratory transportation. The litter items were kept at environmental temperatures while being transported.

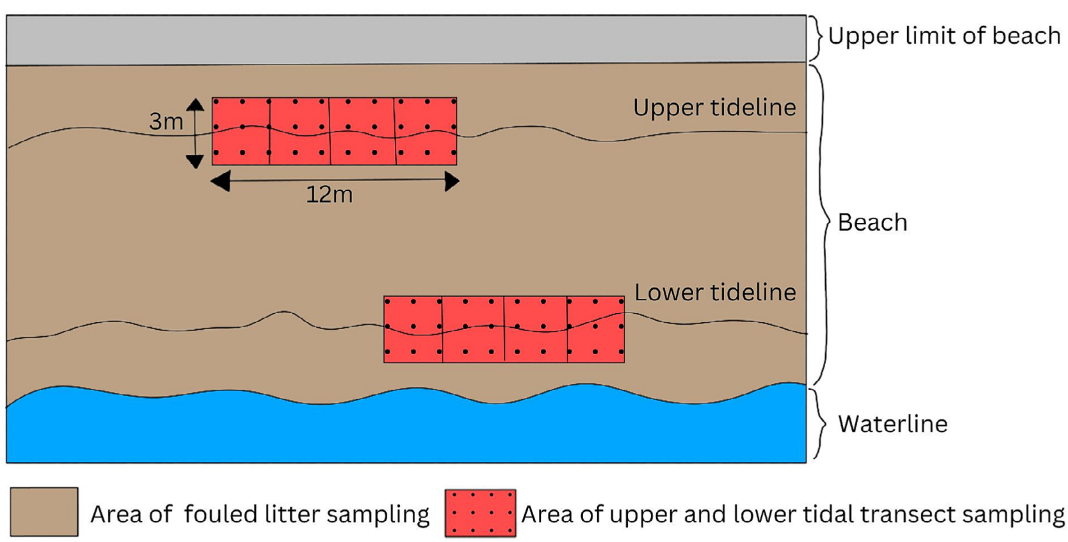

Figure 2. Survey areas of fouled litter sampling and upper and lower transect sampling.

The second type of survey conducted at each site looked at both fouled and non-fouled litter items in standardised transects along the upper and lower tidal line, with these transects serving as a subsample for the entire beach. The upper and lower tidal transects were parallel to the shoreline and comprised of four joined 3x3 m^2 quadrats (Figure 2) and were measured at each site immediately after high tide. The areas selected for the transects were chosen after visual inspection, ensuring they represented sections of the beach with typical accumulations of natural and anthropogenic litter. This visual assessment method was selected to mitigate bias arising from the small transect areas and limited replication given that beached marine litter is often heterogeneously distributed along shorelines (Velander and Mocogni, 1999; Brown et al., 2015; Rech et al., 2018). This survey aimed to identify the composition of litter in the upper and lower tidal lines of each beach, distinguishing between recently and less recently beached marine litter based on shore height. Recently beached litter was expected to accumulate near the lower tidal limit, whereas less recently beached litter was expected to be found at the upper tidal limit. Each transect was measured and its boundaries delineated on the beach. All macro litter items (>1.5 cm in size) within the transects were counted and their material was recorded and classified according to the DeNIS protocol. These items were not collected for further laboratory analysis. The origin of land- or sea-based litter was determined following UNEP guidelines, which categorise litter into five main sources: (1) the Fishing industry, including aquaculture; (2) Galley waste (non-operational waste from shipping, fisheries, and offshore activities); (3) Shipping, including offshore activities (operational waste); (4) Sanitary and medical waste (sewage related waste); and (5) Public littering (tourism and other recreational activities) (UNEP, 2009).

In the laboratory, the collected litter items from the first survey were gently rinsed with fresh water to remove sediment and loose debris. The litter items were then kept hydrated in seawater to maintain the potential viability of living organisms. All attached organisms were counted and detached from the litter using forceps or scissors. Subsampling occurred in the case of high uniform abundance on a litter item, during which organisms were continuously inspected through a stereoscope to confirm that all species were removed, identified, and accounted for to avoid compromising diversity counts. Furthermore, only encrusted or otherwise attached organisms were included in species counts, as organisms with higher degrees of mobility create uncertainty about whether they were attached to the litter or moved onto it after washing ashore. Subsequently, organisms were stored according to three procedures: 1. Dehydrated organisms were kept dry and stored in a vial without liquid. 2. Organisms found live but not intended for genetic analysis were stored in vials with 70% ethanol. 3. Organisms found live and in pristine conditions were stored in vials with 96% ethanol for future DNA analysis.

The morphology of the attached organisms was visually assessed using a stereoscope, leading to classification into their respective taxonomic groups under the guise of several taxonomy books (Ryland and Hayward, 1977; Hayward and Ryland, 1979; Hayward, 1985; Hayward and Ryland, 1985; Hayward and Ryland, 1990a; 1990b) and various academic online sources such as peer-reviewed journal articles (e.g., Schuchert, 2000; 2001). Visibly fragmented pieces of organisms were not counted towards total abundance due to the uncertainty of fragments being pieces of a fully intact organism.

Analysis

To identify the type and origin of the collected rope, cord and lines, photographs were organised by region (Southwest, Westfjords and Northeast), compiled into a document and sent to professionals knowledgeable about the fishing gear used in Iceland. The gathered information was then analysed to determine whether a specific fishing sector or type of gear was a significant contributor to the fisheries-based litter found during sampling.

One-way analysis of variance (ANOVA) was used to test significant relationships between material types, surface rugosity (textured/ smooth) and thickness (flexible/ solid) against species abundance and species richness among the collected fouled marine litter. If the logged data failed to conform to a normal distribution, the Shapiro-Wilks test was conducted using a threshold p-value of 0.05 to indicate significance. If the values still failed to meet the assumptions for an ANOVA test, the Kruskal-Wallis test was carried out with a threshold p-value of 0.05 for significance. Whenever the ANOVA assumptions were met and the p-value was lower than 0.05, a Tukey ad hoc test was performed to determine which comparisons were statistically significant. Furthermore, species richness, diversity and species evenness were compared to determine which region had the highest ecological values (De la Torre et al, 2021). The Margalef‘s species richness index was used as a measure of the number of species in a community (Margalef, 1958). The combined use of the Shannon-Weaver and Simpson‘s diversity indices were chosen as the Simpson’s index highlights dominance and inequality within a community, whereas the Shannon-Wiener index provides insights into overall diversity and species evenness (Simpson, 1949; Shannon and Weaver, 1963). A comprehensive understanding of community composition and diversity patterns can be achieved with the use of both indices. Lastly, the Peilou's species evenness index was used as it qualifies the relative abundance of the varying species in a community (Pielou, 1966).

RESULTS

Marine litter

In total, 702 fouled items of marine litter were collected during the shoreline surveys, with an additional 276 pieces of fouled and non-fouled litter being observed during the transect surveys. The highest numbers of fouled litter items were recorded in the Southwest region, followed by the Northeast and then the Westfjords. The number of fouled litter items per 10-m segments ranged from one to 37 (Figure 3). Plastic emerged as the predominant material type among fouled items across all three regions, with the highest concentration found in the Southwest, followed by the Northeast and then the Westfjords. Among the fouled litter items, cord, rope and sanitary towels/panty liners/backing strips showed the largest proportions. Textile was the second most common type of fouled litter collected across the three regions, with the highest amount found in the Southwest, followed by the Northeast and lastly the Westfjords. The most common textile items found were textile cord/net/rope, clothing/rags and unidentified textile pieces. Fouled paper, metal and medical items were relatively uncommon. Fouled paper items were only found in the Southwest region, whereas fouled metal items were found in Southwest and Westfjords regions and fouled medical items were only found in the Northeast region. The abundance and material type of a litter item showed a statistically significant difference between paper/plastic, textile/paper, and paper/metal ($P < 0.001$) (Figure 4, Table 1).

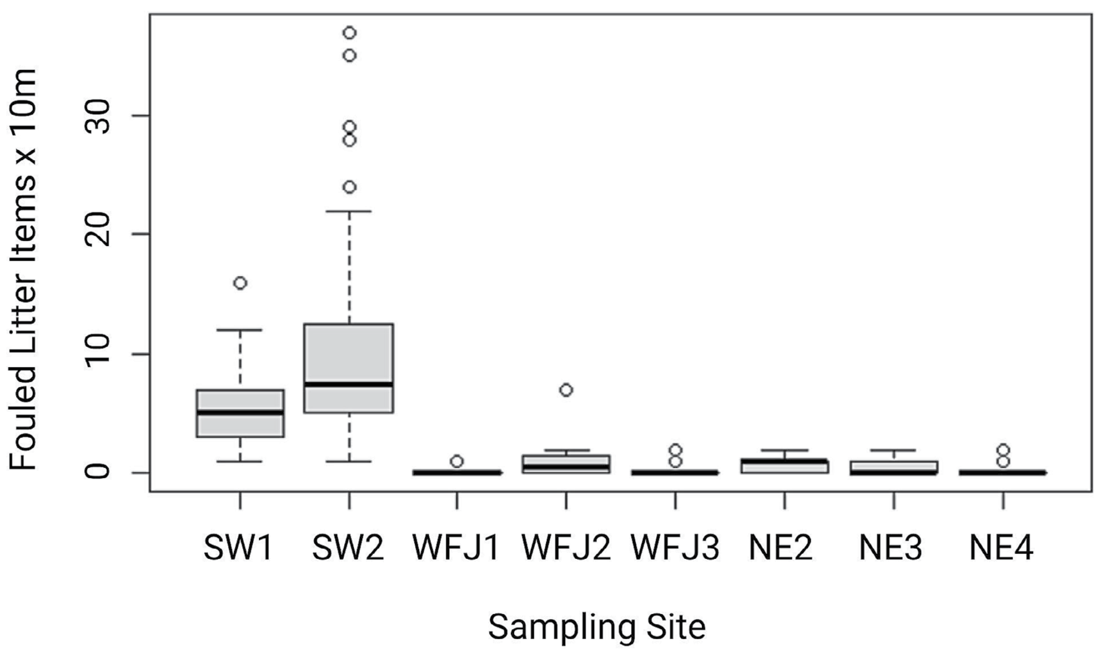

Figure 3. Number of fouled litter items collected in each 10-m segment at each sampling site. The horizontal bar indicates the median of rate distributions. The boxes indicate the quartiles. The dotted lines indicate 1.5 times the interquartile range. Circles indicate outliers. SW – Southwest, WFJ – Westfjords, NE – Northeast.

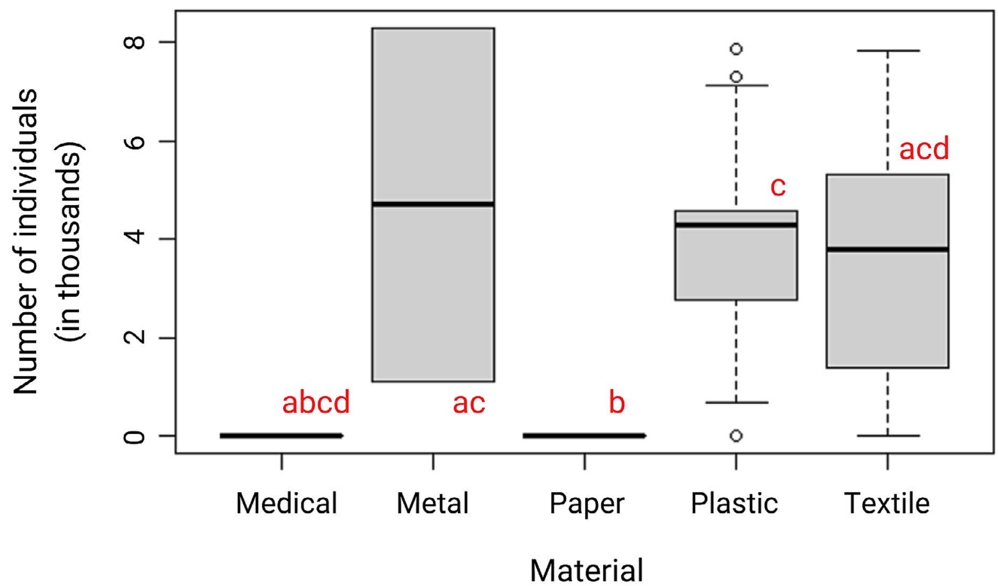

Figure 4. Number of individuals found on fouled litter items by material type. The dotted lines indicate 1.5 times the interquartile range. Circles indicate outliers. Boxes that share a letter have no statistically significant differences.

Regarding surface rugosity and thickness, textured and flexible litter items were the most commonly found fouled litter in all three regions (79 – 96%) followed by smooth and solid items (2 – 17%) and smooth and flexible items (2 – 5%), whereas textured and solid items were absent from the survey. An ANOVA test was used to determine the presence of a statistically significant relationship between the surface rugosity and thickness of a litter item and its abundance. Results showed that textured/flexible litter and smooth/solid litter had a statistically significant difference in abundance ($P < 0.001$) (Figure 5, Table 1).

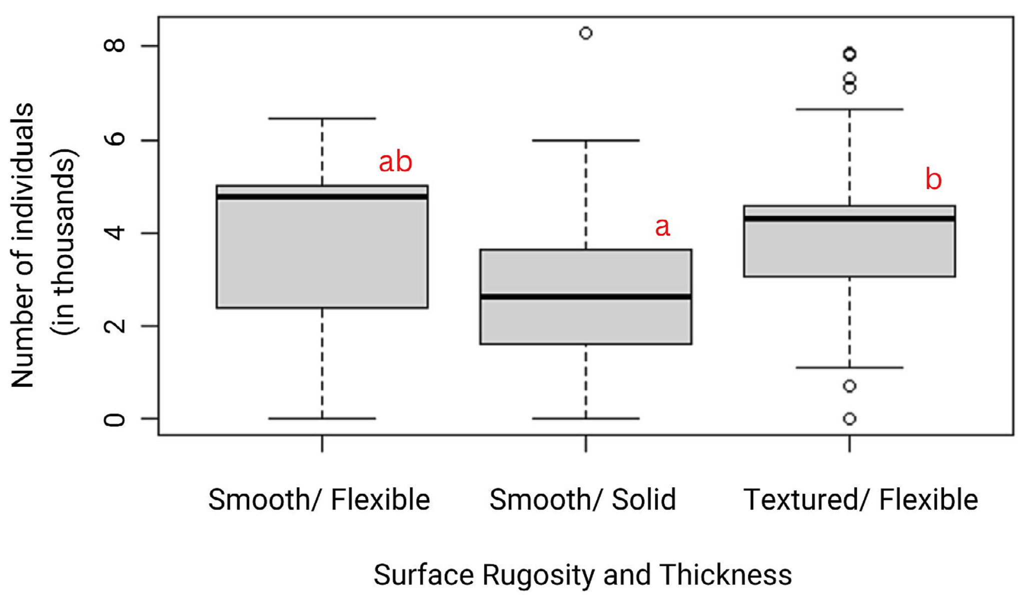

Figure 5. Number of individuals found on fouled litter items according to surface rugosity and thickness. The dotted lines indicate 1.5 times the interquartile range. Circles indicate outliers. Boxes that share a letter have no statistically significant differences.

Table 1. Detailed statistical results for each comparison tested. Df = degrees of freedom, SS = sum of squares, MS = mean sum of squares, F = value of F distribution, P = P-value associated with the F-value. The bolded P-values are less than the alpha value of 0.05 indicating statistical significance.

Number	Test type	Variable	Factor	Df	SS	MS	F	P
1	ANOVA	Species Richness	Region	2	11.6	5.8		
			Residuals	60	69.6	1.2	5	0.010
			Total	62				
2	ANOVA	Abundance	Region	2	316.1	15.8	71.4	<0.001
			Residuals	672	1487.5	2.2		
			Total	674				
3	Kruskal-Wallis	Species Richness	Material Type	27	-	-	-	0.260
4	ANOVA	Abundance	Material Type	4	62.8	15.7	6	<0.001
			Residuals	670	1740.8	2.6		
			Total	674				
5	ANOVA	Species Richness	Surface Rugosity & Thickness	2	4.3	2.2	1.7	0.195
			Residuals	60	76.9	1.3		
			Total	62				
6	ANOVA	Abundance	Surface Rugosity & Thickness	2	44.6	22.3	8.4	<0.001
			Residuals	674	1781.2	2.6		
			Total	676				

Of the 702 collected fouled litter items, 552 items were sea-based (ropes, cords, buoys, fishing floats and longline hooks) relating to the fishing industry and 150 items were land-based from mismanaged land waste (food wrapper and plastic bags), sewage (sanitary towels/panty liners/backing strips, tampons and wet wipes), recreation (shotgun cartridges) or industrial sources other than fishing (plastic sheeting, metal scraps, palettes, and scrap wood). In the Southwest, 84% of fouled plastics were from the fishing industry, compared to 62% in the Northeast and 50% in the Westfjords. For fouled textiles in the Southwest, 65% were linked to fishing, whereas the Westfjords had 100% and the Northeast had none. Paper, metal and medical items had no association to the fishing industry in any of the regions. The Southwest had the highest proportion of fouled litter linked to fishing at 82%, followed by the Northeast at 57% and the Westfjords at 52%.

In the Southwest region, the following fishing-related litter was identified: Cordelia rope, Ione longline rope, longline rope produced before 1998, rope used for closing a cod end on a trawl or Danish seine, nylon hand jiggling line, gillnet entanglements, PE twine used in bottom trawls, polyethylene (PE) perlon twine, old textile trawl net, seine net, tangled trawl nets and multi-braided rope. In the Westfjords, the following fishing-related litter was identified: Krafttóg PE rope, shrewd line, bottom trawl PE net, longline produced before 1987, PE braided rope commonly used to tie ships to the quay and PE rope to repair trawl nets. In the Northeast region, the following fishing-related litter was identified: PE cord used to repair net trawls, PE rope, twine, and trawl net entanglement, general use rope, trawl rope and PE ropes from fishing seine. Moreover, a nylon over-braided or PE rope from a sailing boat was identified. This is unsurprising as the site in which it was collected was near the Nökkvi sailing club in Akureyri, North Iceland.

Upper tidal transects had a higher number of fouled and non-fouled litter in relation to the lower tidal transects in all regions. Upper tidal transects included individual litter items composed of plastic, glass/ceramics, wood, paper, textile, rubber, metal and medical items. In contrast, lower tidal transects contained these same materials excluding wood and medical materials. In both upper and lower transects, plastic was the dominant type of litter material in all three regions, with upper tidal transects having more litter found. In the upper tidal transects, the Northeast sites were the most littered with 140 total items found, followed by the Westfjords with 93 items and the Southwest with 57 items. In the lower tidal transects, the Southwest was the most littered, with 25 items found, followed by the Westfjords with 18 items and the Northeast with 13 items. Altogether, more litter was found in the upper tidal transects in all regions (N = 221) when compared to the lower tidal transects (N = 56).

Fouling species

In total, six phyla were identified from the fouled litter during the full beach surveys: two species of Annelida, six species of Arthropoda, 44 species of Bryozoa, two species of Chordata, 33 species of Cnidaria and five species of Mollusca. Cnidaria had the highest number of individuals in the Southwest (69%) and Northeast (86%), but Annelida had the highest abundance in the Westfjords (31%).

More than 79,000 individuals belonging to 92 species were found on fouled litter at the eight sites surveyed (Table S1). *Mytilus edulis* was found at all sampled sites, while *Abietinaria filicula* and *Dynamena pumila* were found in seven and *Abietinaria abietina*, *Electra pilosa*, *Symplectoscyphus triqueter* and *Tricellaria ternata* were found at six, evincing the most common species in all regions. The species with the highest individual totals per region were *Abietinaria filicula* (N= 27,084), *Spirorbis* (*Spirorbis*) *spirorbis* (N= 22,951) and *Hydrallmania falcata* (N= 11,758) in the Southwest; *Spirorbis* (*Spirorbis*) *spirorbis* (N= 118), *Turtonia minuta* (N= 54) and *Mytilus edulis* (N= 45) in the Westfjords; and *Obelia dichotoma* (N= 392), *Abietinaria abietina* (N= 339) and *Symplectoscyphus tricuspidatus* (N= 268) in the Northeast. The Northeast had the lowest species richness (20 species) followed by the Westfjords (32 species) and the Southwest (87 species). The Southwest had the highest abundance of identified individuals (N= 77,696) followed by the Northeast (N= 1,557) and the Westfjords (N= 379). Although the Westfjords had the highest phyla evenness, the Southwest had the highest species richness and abundance of individuals.

Results indicated a statistically significant difference in species richness between the Southwest and Westfjords regions ($P < 0.01$) (Figure 6, Table 1). Additionally, statistically significant differences in abundance were observed between the Southwest and Northeast regions, as well as between the Westfjords and Southwest regions ($P < 0.001$) (Figure 7, Table 1).

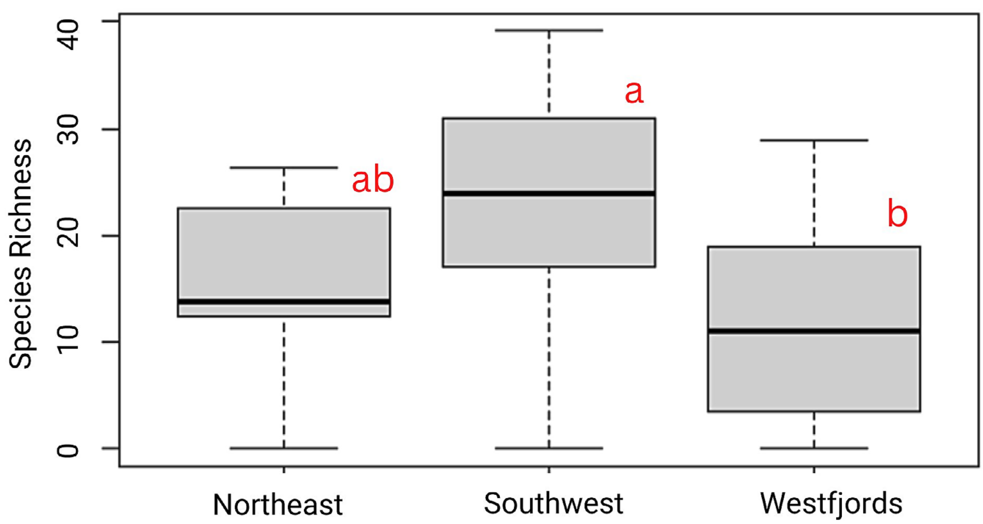

Figure 6. Species richness on fouled litter items by region. The dotted lines indicate 1.5 times the inter-quartile range. Circles indicate outliers. Boxes that share a letter have no statistically significant differences.

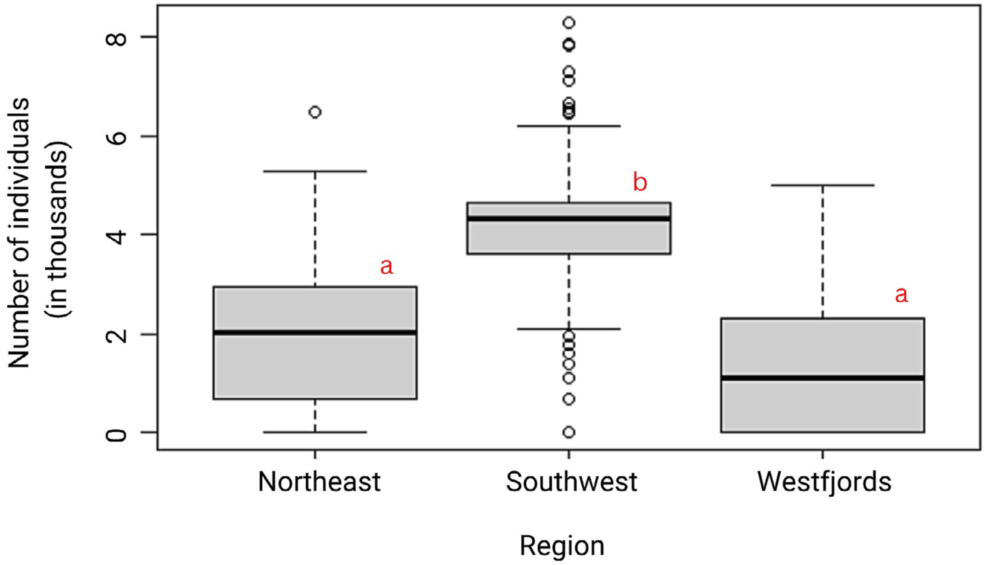

Figure 7. Number of individuals found on fouled litter items by region. The dotted lines indicate 1.5 times the interquartile range. Circles indicate outliers. Boxes that share a letter have no statistically significant differences.

The results of Margalef's species richness index show that the Southwest region has the highest species richness (10.03), followed by the Westfjords (5.55) and the Northeast region (2.82) with the lowest species richness. The Shannon-weaver diversity index indicate that the Westfjords have the highest diversity (2.45) among the three sampled regions, whereas the Southwest and Northeast regions have the same diversity value (1.98) (Table 2). The results of the Simpson's diversity index indicate that the Westfjords have the highest diversity (0.86), followed by the Northeast (0.83)and the Southwest region (0.77). This means that there is an 86% probability that two randomly chosen individuals in the Westfjords belong to different species, an 83% probability in the Northeast and a 77% probability in the Southwest. Results of Pielou's species evenness index show that the Westfjords had the highest species evenness (0.70) of the three regions, followed by the Northeast (0.64) and the Southwest region (0.42), which had the lowest species evenness.

Table 2. Numerical results of ecological indices. Bolded values indicate the region with the highest species richness, species diversity and species evenness according to the rules of each index.

Index	Ecological community characteristic	Region	Value
Margalef	Species richness	Southwest	10.03
		Westfjords	5.55
		Northeast	2.85
Shannon-Weaver	Species diversity	Southwest	1.98
		Westfjords	2.45
		Northeast	1.98
Simpson	Species diversity	Southwest	0.77
		Westfjords	0.86
		Northeast	0.83
Pielou	Species evenness	Southwest	0.42
		Westfjords	0.70
		Northeast	0.64

DISCUSSION

Plastic was the most fouled material type of marine litter found across all regions in this study. This finding agrees with previous research as it found plastics as the most common substrates for rafting (Póvoa et al., 2021; Kannan et al., 2023), corroborated by studies conducted by Rech et al.'s (2018) and De la Torre et al.'s (2021), who used similar methodologies. In both cases, the abundance of fouled plastics exceeded that of other materials. This prevalence may be attributed to the sheer quantity of plastic items in the marine environment, which are highly susceptible to fouling due to their buoyant, persistent, and durable nature when compared to other materials (Worm et al., 2017; Rech et al., 2018; Aretoulaki et al., 2020). Furthermore, Pinochet et al. (2020) found that invasive bryozoan larvae (*Bugula neritina* and *Bugulina flabellata*) preferred plastic substrate over concrete and wood during their pre-settlement larvae stage. Their study found that larvae exposed to plastic surfaces showed reduced swimming activity increased exploration, indicating a preference for plastic and lower energy expenditure during habitat exploration (Pinochet et al., 2020). This preference resulted in a rapid settlement rate, with 50% of larvae settling on plastic after only five minutes (Pinochet et al., 2020). Higher energy expenditure during settlement could potentially limit resources available for colony growth once established (Pinochet et al., 2020). Therefore, the ability of fouling organisms to travel considerable distances via marine litter, alongside the possibility that larvae of certain invertebrate species prefer plastics substrates might extend the range of distribution for fouling species.

Textured/flexible litter and smooth/solid litter had a statistically significant difference in abundance, meaning they were fouled to a higher degree in comparison to smooth/flexible litter. Items with textured/flexible surface rugosity and thickness were also found in higher quantities in all regions, followed by smooth/solid items, and finally, smooth/flexible. These results propose that fouling species prefer textured/flexible and smooth/solid marine litter. Textured/flexible items may show a higher fouling abundance due to their tendency to entangle Hydrozoans and tubular bryozoans, indicating a potential preference for these substrates. These hydrozoans and tubular bryozoans can attach to the substrate by entanglement, subsequently rooting and colonising the litter. Despite this substrate being flexible, some fouling species have physiological adaptations, such as flexible bodies, that enable them to move in tandem with the material. In contrast, hard-bodied species may break due to their lack of flexibility. Typical smooth/solid fouled litter included hard plastic buoys, fishing floats, bottles, and metal fragments. These types of litter were found in lower quantities than those of textured/flexible litter. However, they were fouled in high abundance, suggesting that fouling species may also prefer this type of surface rugosity and thickness. Fouled smooth solid substrates were in large unbroken pieces, granting extra surface area for larvae settlement and subsequent colonisation. Additionally, fouling communities may be attached to textured/flexible items due to the high number of litter with textured/ flexible characteristics on the sampled beaches. Therefore, multiple variables regarding the characteristics of litter beyond surface rugosity and thickness must be examined to determine conclusive patterns.

In total, 702 fouled items of marine litter were collected under full shoreline sampling and 276 pieces of fouled and non-fouled litter were observed under transect sampling. At the sampled sites, possible input sources include sewage outfall pipes, surrounding industries, recreation, mismanaged land waste, and offshore fishing operations. Litter such as sanitary towels/panty liners/backing strips, tampons and wet wipes were collected from sewage outfall pipes. In Southwest and Westfjords sites, sewage outfall pipes were located alongside several beaches. Sewage-related litter was often fouled, likely due to its textured/flexible surface rugosity and thickness, which commonly entangling fouling communities. Surrounding industries made a noticeable impact on the marine items that were collected and identified at each site. This finding is in line with Rech et al.'s (2018) study, which observed that sites close to industries had the highest levels of pollution.

Typically, sampling sites with immediate proximity to industries had the most evidence of this. For example, sites SW1, WFJ1, WFJ2, WFJ3 and NE2 were directly affected by this, whereby site SW1 was adjacent to a now abandoned fish oil factory, resulting in the uncovering of numerous ceramic fragments. Recreational litter was scarcely found at the sampled sites. Aside from shotgun cartridges, litter created by recreational activities was difficult to detect. Cartridges were found fouled and non-fouled, most of which were non-fouled. Mismanaged land waste was a noticeable source of fouled and non-fouled litter at the sampled sites. This included food containers, drink bottles and cans, hard and soft plastic fragments and plastic bags. General household waste items such as these were found near residential areas. It is common for residential and public garbage and recycling bins to be knocked over and opened during periods of high wind. If inadequately secured, litter may enter marine and coastal environments. However, uncertainty remains whether mismanaged land waste entirely stems from weather blowing over bins and releasing litter or from public littering.

Marine litter items with identifiable markings distinguishing the country of origin were scarce. Items with clear markings that indicate provenance were one reusable bag and one fishing float, both of which point to Iceland as its country of origin.

The results of this study indicate that sea-based litter accounted fro the highest proportion of fouled litter, while land-based accounted for the lowest. In contrast, previous studies in Spain (Rech et al., 2018), Peru (De-la-Torre et al., 2021), the Moroccan Mediterranean (Mghili et al., 2022) and India (Kannan et al., 2023) found higher quantities of fouled land-based litter compared to sea-based litter. This discrepancy may arise from the challenge of determining the origin of certain items as sea-based litter can also include household items brought onto vessels and lost at sea (Bergmann et al., 2022). De-la-Torre's (2023) study also found this to be a common occurrence while surveying beached marine litter, suggesting that a significant number of bottles may be discarded by ships offshore, though it is impossible to definitively point their origin to either source. Typically, sea-based litter is immediately deposited into offshore areas and into the ocean by activities such as fishing, aquaculture or shipping. In contrast, land-based litter gradually moves into the marine environment by activities such as public littering or mismanaged waste and is usually deposited closer to the shoreline (Derraik, 2002; UNEP 2009). This immediate deposit of litter into offshore marine environments suggests that marine litter may exist in the water longer, providing a longer opportunity for fouling organisms to attach to it before beaching. Moreover, sea-based litter items (such as nets, ropes, fishing floats and buoys) are designed to be persistent and sometimes buoyant in water due to the nature of their usage. The buoyancy and durability of these items enables them to travel further distances without experiencing high levels of rapid degradation, thus accumulating more fouling species over time and distance (Enrichetti et al., 2021; Kannan et al., 2023). Furthermore, this study found that fouling organisms showed a preference for sea-based litter over land-based litter.

When comparing the marine litter under the transect methodology, land-based litter was found in higher quantities than the sea-based one, indicating that land-based litter was polluting the sampled beaches more frequently than sea-based litter. Due to the high occurrence of land-based litter on the sampled beaches, one would expect this type of litter to experience a higher fouling frequency, but this was not the case. Land-based litter in coastal areas may have two categories, one that has been exposed to the ocean and one that is yet to be exposed to the sea. Land-based litter that enters the ocean can be fouled by species such as barnacles and Bryozoa, which typically adhere to hard substrates. As this litter remains in the marine environment for some time, these species reproduce, making it susceptible to colonisation and fouling. Conversely, land-based litter that is yet to be exposed to the marine environment may remain unfouled due to the absence of sessile fouling species and the lack of time spent in the ocean. Therefore, it avoids colonisation by hard substratum species as it is yet to be exposed to them. The absence of beach species fouling the litter suggests that colonisation, rather than occurring where the litter is found, does so in the environments it previously occupied. Thus, land-based litter fouled by hard substratum species upon washing ashore indicates prior colonization in the marine environment. This underscores that land-based litter must persist in the marine environment for a period to be fouled by the hard substratum species identified in this study. Therefore, the ability of fouling organisms to travel considerable distances via marine litter, coupled with the possibility that larvae of certain invertebrate species prefer plastic substrates, may extend the distribution range of fouling species. Additionally, this is in line with the research by Kannan et al. (2023), which found higher species diversity on plastic litter, attributed to its greater abundance, prolonged presence, and persistence in the marine environment.

The phyla Annelida, Arthropoda, Bryozoa, Chordata, Cnidaria and Mollusca were identified in this study. These phyla show physiological and feeding adaptations that include specialised mechanisms for substrate attachment, sedentary or sessile lifestyles, suspension or filter feeding and reproduction strategies that require no movement (asexual budding, spawning and hermaphroditism) (Buckeridge & Reeves, 2009; Allen et al., 2017). Attachment to a substrate is a defining characteristic of fouling species, making effective anchoring critical (Póvoa et al., 2021). Interestingly, these phyla successfully attach to marine litter using various methods, such as byssal thread attachment, cementing by secretion and anchoring via foothold (Allen et al., 2017). Mechanisms of attachment to litter items vary across the identified phyla. Annelids use permanent calcareous tubes composed of crystalline calcium carbonate with a mucopolysaccharide matrix for substrate adherence (Pechenik, 2015; Rzhavsky et al., 2018). Barnacles utilise their foot to create a strong anchor point (Pechenik, 2015). The identified Bryozoa have an exoskeleton that cements or anchors them to substrates (Hageman et al., 1998). Tunicates utilise a cellulosic tunic that forms an integumentary matrix on substrates (Hirose and Sensui, 2021). Hydrozoans use basal disks and hollow tubular structures (stolons) for attachment (Gili and Hughes, 1995; Bouillon et al., 2006; Pechenik, 2015). Lastly, the identified bivalves employ byssal threads to anchor themselves to substrates (Penchenik, 2015).

Remarkably, *Chorizopora brongniartii* (Audouin, 1826) was identified in this study. This species has only recently been found in Icelandic water and has been classified as non-indigenous (Micael et al., 2022). Apart from polar waters, *C. brongniartii* is generally considered cosmopolitan and has only been collected in Icelandic waters since 2015 (Hayward and Ryland 1999; Berning 2006; Souto et al., 2014; Gíslason et al., 2017, Micael et al., 2022). The persistent occurrence of this species in Iceland indicates its establishment and ongoing presence in Icelandic waters. However, knowledge on the species itself and the specific ecological factors that have facilitated its establishment in this sub-arctic region remains limited. The detection of *C. brongniartii* highlights the potential for non-indigenous bryozoans to establish themselves on marine litter in Icelandic waters. As research in this area grows and taxonomic identification becomes more precise, these findings can inform management strategies that consider the presence of small species such as bryozoans.

Further analysis revealed a substantial disparity in species richness, diversity and evenness of fouled marine litter across the three regions. The Southwest region had the highest species richness, followed by the Westfjords and the Northeast. The Westfjords had the highest diversity and species evenness, followed by the Northeast and the Southwest. The current literature on the richness, diversity and evenness of species on marine litter in Iceland is limited. Although reports on tracking biodiversity trends in the Arctic exist (CAFF, 2010; Bluhm et al., 2011; Fernandez et al., 2014; Eiríksson and Símonarson, 2021), small-scale studies that look at regional differences are uncommon. Therefore, the ecological data from this study could not be used to make further comparisons and connections. However, ecological information may be an important resource in future recommendations for management and monitoring as it provides baseline data and may be considered data to fill current knowledge gaps while introducing the possibility for further research opportunities.

Marine litter is acknowledged as detrimental to marine organisms and the marine environment, leading to its monitoring under CEMP and OSPAR guidelines (OSPAR Commission, 2020). These programs are commonly implemented to reduce the influx of marine litter and facilitate its removal from the marine environment. These guidelines provide monitoring and assessment programs aimed at detecting spatial variations and temporal changes in the litter found in beach monitoring sites (OSPAR Commission, 2020). Additional monitoring programs actively address NIS on shipping vessels, aquaculture-related structures and recreational boating vessels under CEMP and OSPAR guidelines as part of regional indicator monitoring (OSPAR Commission, 2020). Although monitoring marine litter and NIS are essential components of effective marine conservation and management, standardised methodologies are necessary to enhance and streamline research in the field of marine litter biofouling (Rech et al., 2018; Póvoa et al., 2021, De-la-Torre et al., 2021; 2023). Focusing solely on monitoring these factors leaves a gap to be filled by examining fouling organisms found on marine debris.

Sampling was performed over a three-month period and therefore is unable to reveal seasonality patterns, accumulation rates or fouling rates in a specific time frame. Furthermore, this study does not fully represent the entirety of the Southwest, Westfjords and Northeast regions of Iceland. Thus, the collected dataserve as baseline information on fouled marine litter in Iceland. Litter items that were not collected due to inaccessibility led to an underestimation of the total number of litter items and organisms. The potential misidentification of organisms at the species level must also be considered when reviewing the main findings. Lastly, the provenance of all litter items could not be confirmed primarily due to the lack of distinct markings on the collected litter. However, the identified fishing gear was assumed to be of Icelandic origin based on survey identification, considering gear material, type and location. The current methodology design provides insight into the fouling species on beached marine litter in three regions of Iceland, providing groundbase data for further research.

CONCLUSION

Over 79,000 individuals representing at least 92 species from the phyla Annelida, Arthropoda, Bryozoa, Chordata, Cnidaria and Mollusca were found on fouled litter at the eight sampled sites. Notably, Cnidaria had the highest fouling percentage in the Southwest and Northeast regions, whereas Annelida dominated in the Westfjords. This study found that the Southwest region had the highest abundance of the collected fouled litter, whereas the Westfjords showed the highest diversity and species evenness. Furthermore, these major observations align with previous international research. Although the provenance of all litter items was not all identified fishing gear was confirmed to be of Icelandic origin. Statistical data analysis uncovered significant relationships between species richness and region, abundance and region, material type and surface rugosity and thickness. Marine litter is often overlooked in monitoring strategies due to its movement and uncertain presence. However, understanding the fouling species in Iceland fills a significant knowledge gap and refines biota information. Incorporating fouling species monitoring into marine litter programs following OSPAR guidelines and CEMP protocol can provide valuable insights into colonisation dynamics and NIS distribution, and support the development of more effective conservation and management strategies. The presence of fishing-related marine litter, which constitutes over 50% of fouled litter in each region, underscores the need for improved management and reduction strategies in this industry. Enhancing fisheries technologies, gear selection, onboard navigation, and weather forecasting, as well as conducting targeted campaigns, can significantly reduce the impact of fishing gear on marine ecosystems while maintaining the economic benefits of these industries. These results highlight the need to continue monitoring marine litter in Iceland, implement effective management strategies to mitigate its impacts on the marine and coastal environment and understand the fouling communities in Iceland.

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AUTHOR CONTRIBUTIONS

H.A.I.S.: Methodology; Investigation, Formal Analysis; Writing – original draft.

J.M.: Conceptualization; Supervision; Writing - review & editing.

S.G.: Conceptualization; Supervision; Writing - review & editing, maps.

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