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*Article*

# Marine Macro-Plastics Litter Features and Their Relation to the Geographical Settings of the Selected Adriatic Islands, Croatia (2018–2023)

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**Abstract:** Marine litter (ML), encompassing human-made objects in marine ecosystems, poses significant threats to the coasts of some Adriatic islands, despite their remoteness and sparse populations. These islands, reliant on tourism, are particularly vulnerable to ML pollution. This study hypothesized that the natural features of the islands influence ML distribution. It employes an integrated geographic approach combining the results of field survey (via sea kayaking) with various indicators which include: (1) coastal orientation and number density of bays, (2) vegetation exposure and biomass share, (3) island area and number density of bays, (4) bay openness and ML quantity, and (5) bay openness and plastic prevalence in ML. Focusing on islands of Lošinj, Pašman, Vis, and the Kornati and Elaphiti archipelago, the study analyzed data collected over six years (2018–2023). Results highlighted that NW-SE and W-E coastal orientations are particularly susceptible to ML accumulation, especially in the southern Adriatic. Linear Fitting Regression analyses revealed a stronger correlation between number density of polluted bays and the surface area of smaller islands (<10 km²) compared to larger islands (>10 km²). The following findings underscore the need for international collaboration and stringent policies to mitigate ML pollution, ensuring the protection of Adriatic marine ecosystems and the sustainability of local communities.

**Keywords:** marine litter; microplastic; coastline; Adriatic islands; Croatia

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## 1. Introduction

Marine litter (ML) is defined as persistent, manufactured or processed solid substances that are intentionally or unintentionally discarded or left in the marine and coastal environment. ML can originate from human activities on the mainland or at sea which normally is not supposed to end up in the marine environment [1]. The substances that typically make up ML are plastics, rubber, paper, metals, wood, glass, fabrics, various other organic matters, etc. ML mostly floats on the surface but can also be found below the surface. ML is transported by dominant sea currents and winds and eventually can wash up on shorelines (plastic beaching) or it can be deposited on seabed [2]. Over the past few decades marine litter pollution is one of the key problems in conservation of ocean ecosystems [3–5].

One of the first cases of sea pollution which caught the attention of the global public was disposal of nuclear waste in the oceans. Since the introduction of the *throw-away society* concept [6], the plastic litter pressure on the world's oceans has outgrown all the man-made waste issues, including the sea waste.

Since 2007 various multilateral agreements and United Nations (UN) resolutions dealing with the ML issue have been signed, yet their impact seems to be very limited so far (see, e.g., [7,8]). Seven elements were proposed [9] to develop an inclusive global treaty: 1) the adoption of a principle of common but differentiated responsibilities, 2) an adequate scope considering management of land- and sea-based sources, and all stages of the lifecycle of plastics, 3) ML issue in relation to the

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international plastics trade, 4) a financial mechanism to support implementation measures, 5) built-in flexibility to adapt to changes, 6) effective monitoring, reporting and review procedures, and 7) enforcement through incentivizing compliance and deterring non-compliance. These elements were aimed at overcoming the challenges of managing marine plastic pollution [10–12].

Same as in the global oceanic ecosystems, dominant sea currents in the Adriatic Sea are primal transporters of ML, namely Western Adriatic Current (WAC) and Eastern Adriatic Current (EAC). Furthermore, the ML distribution and accumulation is also affected by the main winds as well as by coast's exposure towards the open sea [4,13–17].

The survey of the Adriatic islands recorded the significance of the marine macro-litter pollution at the remote, sparsely inhabited or uninhabited islands, where the anthropogenic impact, e.g., that of distant urbanized areas, has been manifested [18–20]. In accordance with Marine Strategy Framework Directive [1], the concept of marine pollution monitoring has been focused on the following classification: i) quantity and composition of macro-waste on the coast [21,22]; (total amount (kg), kg/m$^2$, and parts /km$^2$); ; ii) litter density (m$^3$/km) [23], and iii) micro-waste in the surface layer of the water column in parts/km$^2$) sea bottom sediment [23,24].

There are two pathways through which plastics enter the oceans, i.e., mainland-based [25] and marine-based sources, each of which contributes 80% and 20% of the total litter, respectively [26,27]. However, no studies have quantified the relative contributions of all critical sea-based sources. Previous ML research on Pašman Island (central part of the east Adriatic coast) showed that the average share of plastic litter was higher at the coastal disposals (55%) than in the inland part of the island (20.9%) [20].

If the current waste production and global waste management trends continue, roughly 12 billion metric tons of plastic waste will be disposed in landfills or in the natural environment by 2050 [3,28,29]. Calculations of the mass of mainland-based plastic litter which enters the ocean estimate that in 2010 275 million metric tons (MT) of plastic litter was generated in 192 coastal countries, with 4.8 to 12.7 million MT entering the oceans and seas [28]. On the other hand, marine-based sources of plastic pollution include commercial fishing, recreational boaters, and offshore oil and gas platforms [30–32].

The aim of this paper is to prove the concept of integral method of indicators, supported by the 6-years field study, as a comparative research method for ML study. After finishing the fieldwork survey, we have combined observed natural settings and ML hotspots features. We registered only hotspots where ML was present in various forms: i) smaller litter scattered on the coastline and ii) large, stranded pieces of litter, e.g., abandoned boats, buoys, parts of furniture, etc.

### *1.1. Study Area*

The Croatian archipelago comprises 1,244 islands, the majority of which are small in area, with only 78 islands exceeding 1 km$^2$. The total coastline length of the islands is 4,398 km, accounting for approximately 70% of Croatia's total coastline [34]. The islands are predominantly composed of carbonate rocks, primarily Cretaceous limestone and, to a lesser extent, dolomites, with occasional occurrences of other deposits, such as flysch and loess. Consequently, the island coastlines are mostly rocky and rugged, with pebble and sandy beaches occurring sporadically. These beaches are particularly significant for local tourism [35].

Of the 1,244 islands, only 50 are permanently inhabited, with a total population of 120,434, according to the 2021 census. This represents approximately 3.1% of Croatia's total population of 3,871,833 recorded in the same year [35]. However, the population dynamics of the islands exhibit significant seasonal fluctuations due to tourism, with the summer population of some islands increasing by a factor of five or more. The long and complex coastlines of the islands create favourable conditions for marine litter (ML) accumulation, particularly in sheltered bays and coves. At the same time, the inaccessibility of many areas poses significant challenges for effective ML management.

The occurrence and distribution of ML are influenced by various atmospheric and oceanic processes, including prevailing winds, wave action, and sea currents. The Adriatic Sea, the northernmost semi-enclosed basin of the Mediterranean, covers approximately 1/20 of the Mediterranean's total area. Its distinct shape and geographic location play a critical role in shaping air and sea circulation patterns, which in turn govern the movement of ML within the region.

Surface sea currents in the Adriatic Sea generally exhibit a cyclonic (counterclockwise) circulation pattern, predominantly driven by prevailing winds with marked seasonal variability in both direction and intensity [13]. During summer, a north-westward current flows along the western Adriatic coast, reinforced by dominant north-westerly winds. In autumn, the frequency of strong southeasterly winds (sirocco) increases, generating a south-eastward current along the eastern Adriatic coast. During winter, the region experiences strong northeasterly winds (bora), particularly on the seaward slopes of the Dinaric Mountains in the eastern Adriatic basin. These bora-induced windstorms generate powerful transverse currents that push water from the eastern to the western portions of the basin [14,15].

### *1.2. Research Sites*

The study sites examined in this research encompass several islands and archipelagos along the northern, central, and southern Croatian coastlines (**Figure 1**). The northernmost site is Lošinj Island, followed by Pašman Island, the Kornati Archipelago, and Vis Island in the central part of the Croatian coast, with the southernmost site being the Elaphite Islands.

Lošinj Island, situated in the northern Croatian coast, is a narrow (maximum width of 5.1 km), elongated island measuring 32 km in length, with an area of 74.37 km² and a coastline length of 121.2 km. It is the most populous of the studied islands, with 7,087 inhabitants recorded in the 2021 census, and hosts the largest settlement on Croatian islands—the town of Mali Lošinj, with approximately 5,500 residents [36].

Pašman Island, located further south, has an area of 60.11 km² and is 21.35 km long with a maximum width of 4.72 km and a coastline length of 70.2 km [37]. The island has a total population of 2,884 (2021 census). Among all the islands included in this research, Pašman is the furthest from the open waters of the Adriatic Sea and is therefore predominantly influenced by marine litter of local origin.

The Kornati Archipelago, located in the central part of the eastern Adriatic coast, consists of 149 islands scattered over an area of 320 km², making it one of the densest archipelagos in the Mediterranean. Since 1980, most of the islands were protected as a national park. A detailed account of the natural features of these islands is provided by Špeh et al. [38].

The island of Vis is located ca. 45 km from the mainland coast in the open water of the Central Adriatic. It covers an area of 89.7 km² which makes it the largest offshore island in the Adriatic Sea. The island is roughly 17 km long and 8 km wide, and the coastline is 84.9 km. Island has a rounded, compact shape unlike most other studied island which are distinctively elongated [39].

The Elaphite Islands are an archipelago in the southernmost part of the Croatian coast, consisting of nine islands, three of which are permanently inhabited. The total population of the archipelago is 985 (2021 census). The islands collectively cover an area of 27 km², while the entire archipelago spans over 90 km² [40]. Due to their proximity to the South Adriatic basin, these islands, along with Vis Island, are the most exposed to marine litter originating from the open sea.

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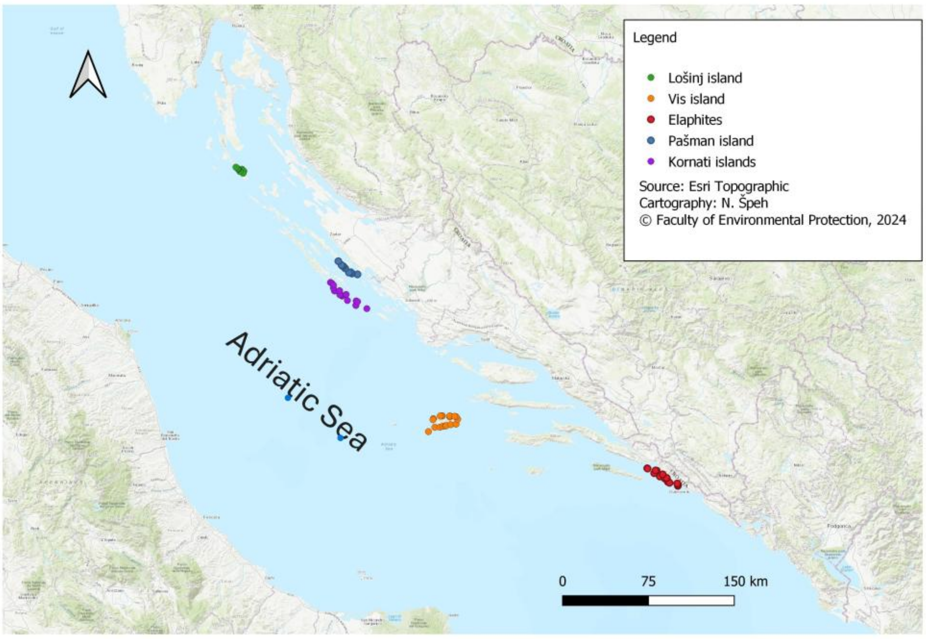


**Figure 1.** Geographic position of the study areas and ML locations in northern, central and southern Croatian Adriatic coast.

## 2. Materials and Methods

Our research involved several extensive field campaigns conducted between 2018 and 2023, primarily during the colder months of the year (autumn to spring). The period was chosen due to the stronger winds and intensified sea currents, which lead to a higher frequency of marine litter deposition on the coasts of the studied islands. Following natural dynamics (meteorological factors and Adriatic Sea currents), ML was never presented as a single incident (please see the attached photo-document below). The ML amount (in $m^3$), biomass proportion (bulky wood, seagrass), and share of plastics were assessed based on an estimated volume of 1 $m^3$ for comparison, without compression or weighing. Other identified ML composition categories included industrial, craft, household, construction, and fishing waste, as well as remains and equipment from vessels. The study introduced the application of transparent and comparative integral geographical indicators. The research methodology consisted of the following systematic steps: 1) survey of published scientific literature on marine macro-litter, 2) selection of the research sites (we recorded every instance of litter deposited along the coast to determine whether the bay or cove was polluted.), 3) determination of physical geographical features significant for ML occurrence and distribution, 4) registering ML locations based on various indicators (ML presence, identification, and composition categories), 5) data analysis (including Pearson correlation with Linear Fitting Regression and Spearman's correlation to connect natural settings and ML characteristics), and 6) graphic presentation of results using GIS.

### *2.1. Indicators Framework*

A set of indicators was developed for use in this research, as similar indicators have been previously demonstrated to be valuable tools for the comprehensive study of marine litter (ML) [41,42]. The selected indicators facilitated the evaluation of the impact of ML on the landscape and established connections between the natural features of ML hotspots and the composition characteristics of the accumulated litter. The set of indicators included: 1) ML location identification: geographic coordinates of ML locations and the designation of hotspots (typically named after bays or coves); 2) bay/cove orientation and exposure: orientation of the bay or cove entrance in relation to cardinal directions; 3) coastal Vegetation conditions: assessment of vegetation along the coastline; 4)

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ML composition: categorization of ML types and their proportional representation in the total ML at each site; 5) Total ML volume: quantification of ML in cubic meters ($m^3$); 6) Plastic ML proportion: calculation of the percentage of plastic within the total ML composition [38]. The values of ML characteristics, including its amount (in $m^3$), the proportion of biomass within ML, and the share of plastics in ML, were assessed after frequency of presence.

Data processing focused on correlating the natural settings of each study site with the collected ML data and determining the existence or absence of statistically significant relationships. To explore potential correlations, the results of the ML site surveys were refined by integrating the following indicators:

1. Coast orientation (relative to the side of world) and total number of bays,
2. Islands surface and number density of the bays/coves (the number of polluted bays per $km^2$),
3. Presence of the vegetation on ML site and the proportion of the biomass in ML
4. Bay/cove orientation and total marine macro litter amount, and
5. Share of plastics in the total amount of ML

### *2.2. Data Processing and Display*

For the cartographic representation of the research areas, we utilized QGIS software [43].

To assess statistical correlations between the landscape characteristics of the hotspots and the indicators of ML composition, we employed a Linear Fitting Regression analysis model. The Pearson ($R^2$) and Spearman's coefficients were used as the determination coefficient to quantify the strength and direction of these relationships [44].

To assess statistical significance and facilitate a comprehensive comparison of observed indicator values, we employed descriptive statistics. One-way analysis of variance was specifically chosen to discern significant differences in the selected indicators across distinct ML locations features, including size of geographical areas (small islands/ large islands vs. number of ML hotspots (number density of polluted coves/bays), and ML composition characteristics (average share of plastic ML per island (in %) vs. ML amount). A significance level of $p \leq 0.05$ was considered statistically significant. The data analyses were executed using Excel 2020 (Microsoft Corporation, Redmond, WA, USA) and open-source statistics JASP package (JASP Software, University of Amsterdam, Amsterdam, the Netherlands, https://jasp-stats.org/), ensuring robust and reliable evaluation of the dataset.

## 3. Results

The presence of ML depositions is shown (with a focus on presence of the plastics) on five Adriatic islands from north to south (**Figure 2a-c**): 1) Lošinj Island, 2) Kornati islands, 3) Pašman Island, 4) Vis Island, and 5) the Elaphites Islands.

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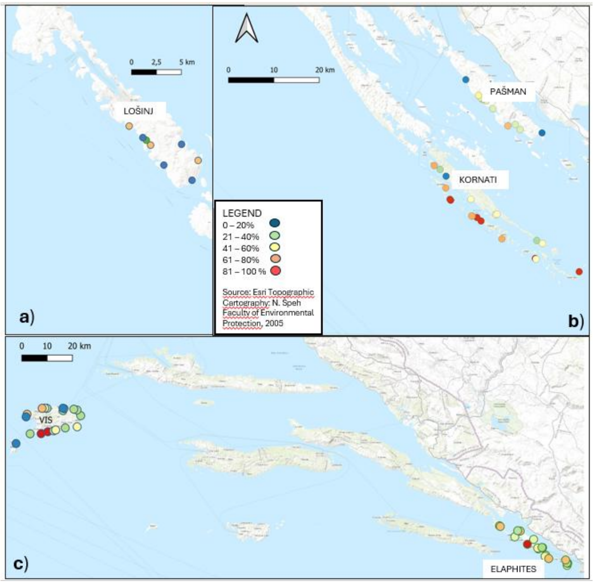


**Figure 2.** The percentage of plastic at ML hotspots on the surveyed Adriatic islands: **a)** Lošinj Island, **b)** Pašman and Kornati Islands, and **c)** Vis and Elphites Islands.

### *3.1. Natural Characteristics Which Determine the Presence and the Distribution of ML*

#### 3.1.1. Indicator 1: Coast Orientation (Relative to the Side of the World) and Total Number of Bays/Coves

Vis Island differs from the other study sites, with bays/coves oriented west-east (W-E) being the most exposed to marine litter (ML) accumulation (47.4%). In contrast, the other studied islands follow the same pattern as the Elaphites and Kornati islands, where coasts with a northwest-southeast (NW-SE) orientation are the most affected by ML accumulation. This is evident on Lošinj Island (62.5%) and Pašman Island (60.0%).

**Table 1.** Number of polluted bays/coves correlated with the orientation of the coast and their share in total number of polluted bays/coves (in %).

| Island(s)/Share (in %) | NE-SW | NW-SE | W-E | N-S | Total (N) |
|---|---|---|---|---|---|
| Elaphites | 5 (27.8) | **8 (44.4)*** | 4 (22.2) | 1 (5.6) | 18 |
| Vis | 4 (21.1) | 4 (21.1) | **9 (47.4)*** | 2 (10.5) | 19 |
| Kornati | 5 (26.3) | **8 (42.1)*** | 4 (21.1) | 2 (10.5) | 19 |
| Pašman | 1 (10.0) | **6 (60.0)*** | 2 (20.0) | 1 (10.0) | 10 |
| Lošinj | 2 (25.0) | **5 (62.5)*** | 1(12.5) | 0 (0.0) | 8 |
| Total | 17 | **31*** | 20 | 6 | 74 |

* The maximum values are in bold.

The total number of registered polluted bays was 74. Analyzing the correlation between coast orientation (relative to cardinal directions) and the total number of polluted bays, we found that the northwest-southeast (NW-SE) orientation of the coast on the studied islands (**Figure 3a-b, Table 1**) was the most exposed to marine litter (ML) accumulation, accounting for 41.9% of the registered ML hotspots. This was followed by the west-east (W-E; 27%) and northeast-southwest (NE-SW; 23%) orientations. Coasts with a north-south (N-S) orientation were the least exposed to ML deposition (8.1%). Among the studied islands, the Elaphites and Kornati showed the greatest similarities in the correlation between coast orientation and ML pollution, with nearly identical proportions of polluted bays/coves with NW-SE orientation: 44.4% and 42.1% of the total number of polluted bays, respectively (**Table 1**).

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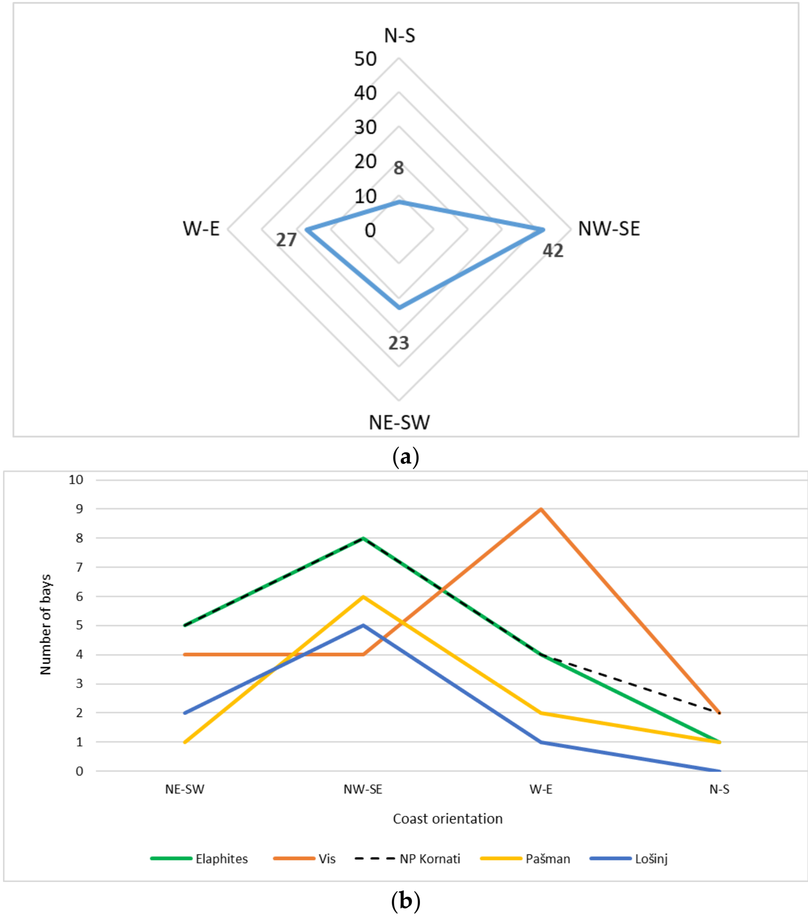


**Figure 3.** Distribution of polluted bays with ML as regards coast orientation: **a)** total number, and **b)** at each researched site.

3.1.2. Indicator 2: Correlation of Coasts with No Vegetation and Biomass Share in Accumulated ML

We identified an unexpected pattern in the appearance of exposed hotspots without vegetation cover and the share of biomass deposited at these sites. To establish this indicator, we combined two features: the vegetation cover at ML locations and the proportion of biomass in the accumulated ML.

The anticipated outcome, that coasts with vegetation cover would also exhibit a higher share of organic litter deposition, was confirmed only for Lošinj Island. This island had the highest proportion of overgrown coasts (50%) and the highest share of biomass accumulation (55%). In contrast, Pašman Island had the lowest proportion of deposited biomass material (42.5%) despite being the second least exposed (70%). On the other hand, all ML hotspots on the Elaphiti Islands were exposed (lacking vegetation), yet nearly half of the marine deposition consisted of organic material (43.5%) (**Figure 4**).

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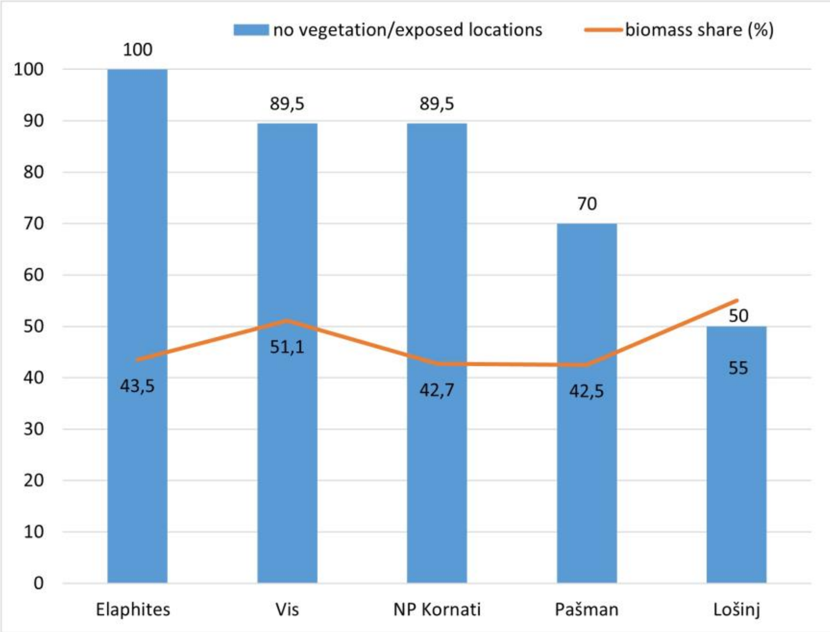



**Figure 4.** Share of locations covered with no vegetation, and biomass share in them.

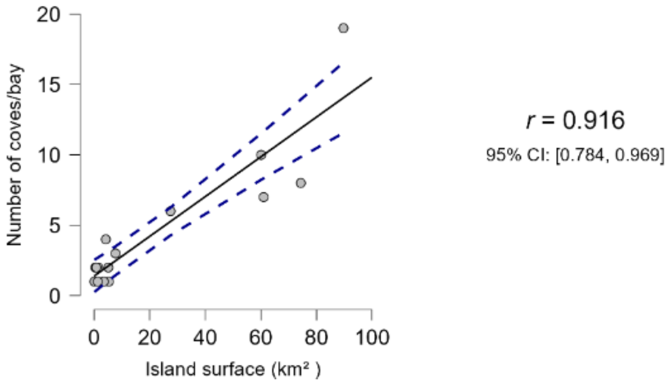
3.1.3. Indicator 3: Islands' Size and Number Density of Bays/Coves with ML

This indicator examines the correlation between island size and the number density of bays/coves with marine litter (ML), expressed as N/km². Meteorological conditions and dominant sea currents suggest that island surface area is not a key determinant of bay/cove number density with ML. Based on available data, the islands were categorized into two groups: (i) small (<10 km²) and (ii) large (>10 km²) (**Figure 5a, 5b**).

The analysis of the geomorphological relationship between island surface area and the number of polluted coves/ bays per island reveals a strong and statistically significant positive correlation (r = 0.916, p < 0.001), at 95% level of confidence (CI) [0.784, 0.969]) for small islands (**Figure 5a**).

| | | | Pearson's r | p | Lower 95% CI | Upper 95% CI |
|---|---|---|---|---|---|---|
| Island surface (km² ) | - | Number of coves/bay | 0.916*** | < .001 | 0.784 | 0.969 |

* p < .05, ** p < .01, *** p < .001




(**a**)

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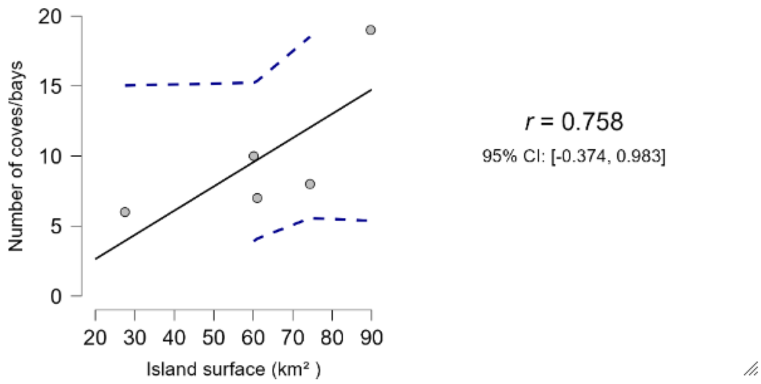
| | | | Pearson's r | p | Lower 95% CI | Upper 95% CI |
|---|---|---|---|---|---|---|
| Island surface (km² ) | - | Number of coves/bays | 0.758 | 0.137 | −0.374 | 0.983 |

* p < .05, ** p < .01, *** p < .001




(**b**)

**Figure 5.** Linear Fitting Regression (trend) analysis of statistically significance between number density of polluted bays/coves and islands' area for small islands, 1 - 10 km² (**a**), and larger area, 10.1-100 km² (**b**).

The Pearson correlation coefficient for larger island is weaker (r = 0.758) and presents moderate statistical significance. We cannot confidently conclude a meaningful relationship between observed variables. P-value is 0.137, which is greater than the typical significance threshold (0.05), and the CI of 95% [-0.374, 0.983] show not statistically important relation 'number density of polluted bays/coves vs. large islands' area' (**Figure 5b**).

*3.2. Marine Macro-Litter Survey*

3.2.1. Indicator 4: Bays/Coves Orientation and ML Quantity

Data on bay orientation and the total volume of marine litter (ML) (in m³) are expected to highlight the significance of natural settings in influencing the accumulation of ML along coastlines. The results, however, revealed a wide range of characteristics and highly scattered data (based on **Figure 6 and Table 2**).

To categorize the ML data, we identified three distinct zones: 1) North Adriatic: Lošinj Island had eight hotspots, with most bay/cove entrances oriented southwest (SW). It recorded the lowest ML quantity (17 m³); 2) Central Adriatic: Pašman Island and the Kornati Islands featured bays/coves with most entrances oriented towards the south. Pašman Island recorded the second-lowest ML quantity, while the Kornati Islands had the second-highest ML quantity, and 3) South Adriatic: Most bay/cove entrances were oriented towards the north. Vis Island recorded the highest ML volume (93 m³), whereas the Elaphites registered 22.3 m³ of ML.

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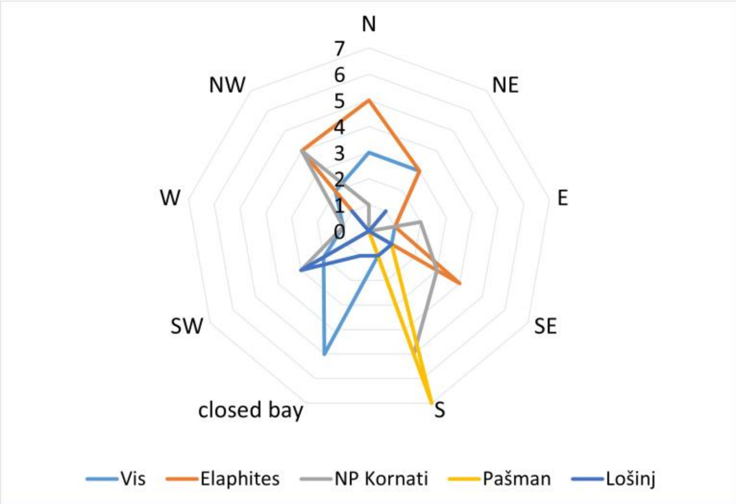


**Figure 6.** Number of bays/coves with registered macro-ML on surveyed Adriatic islands and orien- tation of their entrances.

**Table 2.** The prevailing orientation of bay/cove entrances, the quantity of marine litter (ML) (in m³), the frequency of identified ML categories, and the percentage of plastic in the deposited ML. The ML quantities represent accumulations recorded over a one-year survey period between 2018 and 2023.

| **Island(s) /Indicator** | **Prevailing bays orientation by frequency (decreasing)** | **ML total amount (m³)** | **Frequency of ML (average %)*** | **Presence of plastic in ML (IC+H+C+F) (%)** |
|---|---|---|---|---|
| Elaphites | N, NW, SE, NE | 22.3 | IC 5.8, H 41.1 B 24.2, F 28.9 | 74.2 |
| Vis | closed bay, N, NE | 93.0 | IC 7.1, H 33.4 B 45.7, F 13.7 | 53.7 |
| Kornati | S, NW, SE, SW | 52.8 | IC 2.4, H 51.7 B 35.6, F 10.3 | 52.8 |
| Pašman | S | 18.0 | H 24.5, B 34.0 F 41.5 | 55.0 |
| Lošinj | SW | 17.7 | IC 5.0, H 22.5 B 55.0, F 17.5 | 48.8 |

*industrial, craft (IC), household (H), Construction (C), biomass presence (B), fishing, vessel objects (F).

### 3.2.2. Indicator 4: Macro ML Quantity and Share of Plastics

Geographical differences were observed in the share of plastics within accumulated ML. The Elaphiti Islands, the southernmost study area, exhibited the highest share of plastics (74.2%) despite having the third-lowest total ML quantity. In contrast, Vis Island, the second southernmost survey site and most exposed to the open sea, recorded the highest total ML quantity and the third-highest share of plastics (53.7%). Similarly, the Kornati Islands, located in the north and exposed to the open sea, had a comparable plastic share (52.8%).

As expected, Lošinj Island, the northernmost study area, and Pašman Island, the least exposed to the open sea, recorded the lowest ML quantities (17.7 m³ and 18 m³, respectively). Lošinj Island also exhibited the lowest share of plastics in ML (48.8%).

Linking the results of ML quantity with the percentage of plastic within the ML (**Figure 7**), the Spearman's rho correlation coefficient of 0.100 shows a very weak positive correlation between the total ML amount and the proportion of plastic in it. The associated p-value of 0.950 is substantially above the conventional threshold for statistical significance ($p < 0.05$). The 95% confidence interval, spanning from -0.858 to 0.903, further reflects considerable uncertainty in the correlation estimate.

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| | | | Spearman's rho | p | Lower 95% CI | Upper 95% CI |
|---|---|---|---|---|---|---|
| Litter amount ($m^3$) | - | Average share of plastic ML/island (%) | 0.100 | 0.950 | −0.858 | 0.903 |

* p < .05, ** p < .01, *** p < .001

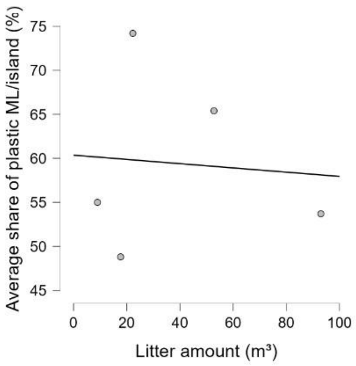


**Figure 7.** Linear Fitting Regression trend correlates the total quantity of ML with the percentage of macroplastics.

## 4. Discussion with Conclusions

Marine plastic waste, accounting for up to 80% of total marine litter, primarily originates from land-based human activities [8,9,19,28]. In this study, we employed a research methodology focusing on the structural analysis of indicators related to marine plastic pollution. Our work contributes to addressing the underrepresentation of marine litter (ML) in environmental risk assessments, e.g., unpredictable long-term impacts on aquatic biodiversity and the ecosystem services it supports [16], and the fragmentation of existing knowledge, as highlighted by Maes [3]. We estimate that our approach yielded significant results, particularly by establishing a link between the natural characteristics of the Adriatic islands surveyed and the accumulation of marine litter in these areas. Moreover, our survey approach was not random but rather a systematic recording of each polluted bay on the studied island. We have not encountered such strong geographical emphasis in previous ML research. In comparison with other ML studies, we recognize an urgent need for: 1) after OSPAR recommendations or the Pacific Regional Action Plan on Marine Litter for 2018-2025, organized ML issue-solving actions in the Adriatic region, focusing on legislation, measures taken, and regional policy obligations, in a way that aligns with 2) the results of continuous research monitoring, including more precise and in-depth guidelines."

Based on the collected data, we introduced five key indicators to assess the distribution of marine litter (ML) and its relationship with geographical and litter-specific features:

**Indicator 1**: **Coast orientation and the total number of bays**. For most islands, coast orientation northwest-southeast (NW-SE) was the most frequently affected by ML deposition, with coverage ranging from 42.1% to 62.5%. This distribution is attributed to waves generated by prevailing southeastern winds, specifically the *jugo/scirocco* winds [45,46]. An exception was observed at Vis Island, where the predominant orientation of ML deposition sites was west-east (W-E; 47.7%).

**Indicator 2**: **Biomass presence**. The proportion of biomass within ML varied between 42.5% (Pašman Island) and 55% (Lošinj Island), with Lošinj also exhibiting the highest share of coastal vegetation.

**Indicator 3**: **Landscape characteristics**. This indicator assessed the relationship between island size and the number density of littered bays/coves. A Linear Fitting Regression model indicated a robust statistically significant positive correlation for small islands (<10 $km^2$, r=0. 916, p <0.001). This suggests that larger islands tend to have more polluted coves/ bays per island, likely due to their more extensive coastlines, when the natural (corrosion of rocks) conditions are adequate.

As regards larger islands' geomorphology (>10.1 $km^2$), a statistically not important significance of correlation was performed (r=0.758, p=0.137). Future research could explore additional variables that impact cove formation, analyse different geographical regions, or apply more advanced statistical models to further refine our understanding of this relationship. Despite these considerations, the findings provide valuable insights into the interplay between island size and coastal morphology.

**Indicators 4 and 5: ML composition and management challenges**. The Spearman's rho correlation coefficient of 0.100 suggests a very weak positive correlation between litter amount and plastic share. The high p-value (0.950) indicates no statistical significance, implying randomness rather than a true relationship. The 95% confidence interval (-0.858 to 0.903) reflects high uncertainty. Data are widely dispersed with no clear pattern, and the nearly flat regression line reinforces the absence of a trend. Thus, no meaningful correlation exists between litter amount and plastic proportion.

However, these indicators highlighted significant seasonal and spatial variations in ML distribution, which complicates management efforts. Islands in the South Adriatic, particularly those with enclosed bays or bays open to the north, recorded the highest ML quantities (e.g., Vis Island: 93 $m^3$) and the highest plastic shares (e.g., Elaphiti Islands: 74.2%). Plastic accumulation was also considerable at the northernmost Lošinj Island (48.8%). These patterns are likely influenced by the proximity to litter sources, such as non-EU countries like Albania and Montenegro in the South Adriatic, where waste management infrastructure and enforcement mechanisms are often inadequate. Additionally, river-borne litter from the Po River in northern Italy contributes to the problem.

Despite extensive global documentation of marine plastic pollution, including data on solid waste, population density, and economic factors, the precise quantification of plastic entering the ocean remains challenging. Our findings, derived from field research designed as a "living laboratory," offer valuable insights for addressing estimation challenges by directly assessing plastic litter presence in the marine environment.

This research also enhances understanding of ML's impacts on both biotic systems (e.g., disruptions to biochemical cycles) and geosphere processes, such as the incorporation of ML into coastal geological structures ("banqueting"). The decline of marine and coastal ecosystem services is expected [47], further exacerbated by climatic factors. Without significant improvements to mainland waste management infrastructure, the cumulative volume of plastic litter entering the oceans is projected to increase exponentially [48].

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