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Morphometric assessment of plastic deposition in a wind-driven marine corridor under bidirectional forces

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ABSTRACT

Plastic pollution poses a growing threat to coastal and marine ecosystems. This study examines the spatial dynamics of plastic accumulation in the coastal area of Kepez Cape, located within the Çanakkale Strait (Türkiye), a bidirectional marine corridor connecting the Black Sea and the Sea of Marmara to the Aegean and the Mediterranean. Due to its exposure to dominant wind regimes (NNE, NE, SW), Kepez Cape offers a valuable natural setting for investigating the interaction between wind and currents in shaping the deposition of plastic debris. Departing from traditional particle count metrics, the study introduces morphometric parameters, surface area and volume, as more ecologically relevant indicators of pollution load. Plastic debris was sampled from three shoreline sectors using standardised transects, and particle dimensions were analysed. Results revealed substantial spatial variability in plastic accumulation, with larger particles found in regions influenced by Black Sea surface currents. These findings highlight the importance of physical forces in shaping deposition patterns and advocate for incorporating surface area-based metrics into coastal plastic monitoring. The study contributes to the development of wind-informed, regionally coordinated monitoring strategies, offering a refined framework for assessing and ultimately reducing plastic pollution in dynamic marine corridors worldwide.

Keywords: Coastal zone pollution, Morphometric analysis, Plastic debris, Surface area of plastics, Wind-driven transport

Introduction

Plastic pollution has become a persistent and growing threat to marine environments. Since the mid-20th century, the rapid growth of plastic materials driven by their affordability, versatility, and durability has resulted in widespread environmental accumulation (Thompson et al., 2009; Gilbert, 2017). Recent global modelling studies estimate that over 53 million metric tons of plastic waste could enter aquatic environments annually by 2030 (Borrelle et al., 2020), highlighting the urgent need for mitigation strategies. The varying levels of plastic accumulation among different fish species reveal notable differences that should be carefully considered, along with necessary measures, for both the marine ecosystem and human health (Mondal et al., 2024). Once released, plastic debris undergoes fragmentation and dispersal influenced by a complex interaction of environmental factors, including wind, wave dynamics, precipitation, coastal morphology, and currents (Jambeck et al., 2015; Lebreton et al., 2018; van Sebille et al., 2020). While microplastics (<5 mm) and nano-plastics (<1 μm) receive considerable attention for their bioavailability and potential for trophic transfer (Gigault et al., 2018; Campanale et al., 2020), macroplastic fragments (>5 mm) remain ecologically significant due to their longevity and impacts mediated by surface area (Andrady, 2011; Delaeter et al., 2022). Coastal areas serve as both zones of deposition and points of re-entry for plastics, depending on the prevailing hydrodynamic forces (Corcoran et al., 2009; Dekiff et al., 2014). Coastal deposition patterns are highly site-specific, shaped by geomorphology, local wind exposure, and current interactions (Isobe et al., 2014; Vousdoukas et al., 2020). As a result, locally contextualised investigations are essential for understanding plastic fluxes and retention, particularly in dynamic transitional environments. The Strait of Çanakkale, part of the Turkish Straits System, connects the Black Sea to the Mediterranean through a stratified bidirectional current regime: surface flow from the Black Sea to the Aegean and a denser undercurrent flowing in the opposite direction (Beşiktepe et al., 1994; Öztürk & Öztürk, 1996). Kepez Cape lies at the centre of this corridor, exposed to three dominant regional wind directions, offering an ideal setting for examining plastic transport mechanisms in a bidirectionally driven marine system.

This study analyses plastic debris accumulation across three wind-exposed shoreline sectors at Kepez Cape in the Strait of Çanakkale. The novelty lies in the use of morphometric metrics, such as surface area and volume, as indicators of environmental plastic load, addressing a gap in traditional count-based assessments. The objectives of the present study are to (i) assess bidirectional transport and retention patterns, (ii) evaluate spatial variability in relation to wind and current regimes, (iii) characterise particle types and colours, and (iv) apply morphometric parameters to infer environmental risks.

Materials and Methods

Study Site and Mapping

The present study was conducted in the Strait of Çanakkale, the southern component of the Turkish Straits System, which serves as a dynamic conduit. Here, the upper current predominantly carries Black Sea waters towards the Aegean, while the lower counter-current transports Mediterranean waters in the opposite direction (Öztürk & Öztürk, 1996). This bi-directional flow plays a crucial role in shaping the distribution and accumulation of plastic debris not only within the strait but also directs the distribution of plastic in a vast water basin extending from the Black Sea to the Mediterranean. Additionally, the Strait's northeast-southwest topographical alignment channels the prevailing wind in the same direction, potentially enhancing the transport of floating debris along its axis.

The cartographic representations in this study were generated by integrating two distinct GIS applications to ensure both accuracy and visual clarity. Ocean Data View ODV version 5.1 (Schlitzer, 2023) was employed for geospatial visualisation and site-specific mapping, while Open Source QGIS (QGIS.org, 2023) was used for all geographical analyses and spatial data processing. To ensure consistency and interoperability, datasets created by QGIS were standardised using ESRI software (Environmental Systems Research Institute, http://www.esri.com). Additionally, coastline delineation was refined through data contributions from OpenStreetMap, enhancing the spatial accuracy of coastal boundary representations. A superimposed illustration of prevailing wind directions for the Çanakkale Strait, based on data retrieved from the Turkish State Meteorological Service (TSMS, 2012) and Arslan et al. (2020), is mapped and presented in Figure 1.

Reflecting the distinct hydrodynamic and ecological characteristics of both the Black Sea and the Mediterranean, the Çanakkale Strait is bordered by a relatively small city and features more extensive natural coastlines compared to the heavily urbanised Istanbul Strait. The Kepez Cape region was selected as the study area due to its location at the point where the Aegean and Mediterranean meet, thereby providing strategic significance for the investigation of marine plastic pollution. Its relative remoteness from dense urbanisation and the absence of significant touristic activities reduce direct anthropogenic inputs, making the study area a valuable site for assessing the transport and deposition of plastic debris.

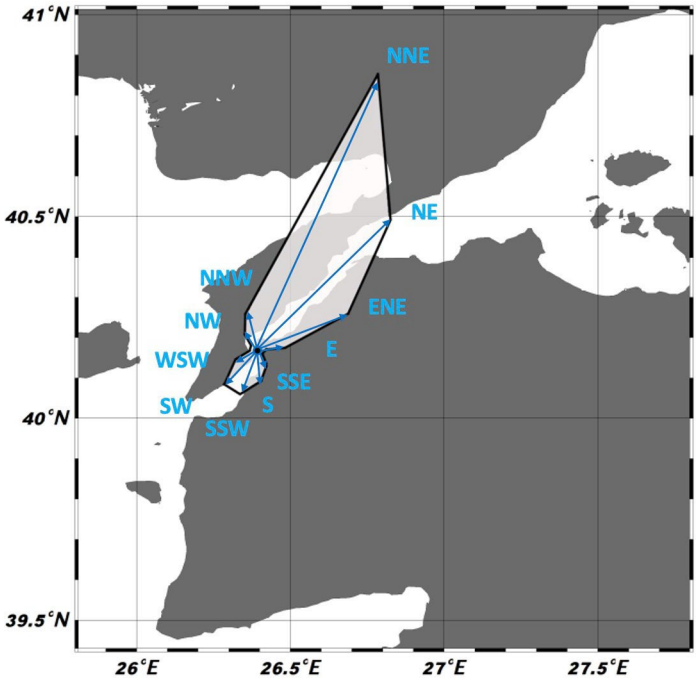

Figure 1. Superimposed illustration of prevailing wind directions in the Çanakkale Strait, produced by Ocean Data View. NNE: north-north-east, NE: north-east, SW: south-west

Sampling

Samples were collected from the Kepez Cape area (Çanakkale, Türkiye) between the geographical coordinates (WGS-84) 40°06'13.83" N and 26°22'14.30" E, and 40°06'14.75" N and 26°22'19.12" E, in April 2024. To ensure comprehensive spatial coverage, three different transects, each 50 m in length, were established along the three shores of the peninsula-like cape. A total of six sampling points were identified, two on each transect, and beach samples were collected by creating 30 x 30 cm quadrats at each sampling point. The Random Points feature in QGIS was employed to minimise potential selection bias (Figure 2).

The sampling locations at Kepez Cape were mapped to illustrate the spatial design of the study. Random sampling points were generated using QGIS along 50 m transects on three coastal sections, each aligned with one of the prevailing wind directions in the Çanakkale Strait, according to data provided by TSMS (2012) and Arslan et al. (2020): north-northeast (NNE, 22.5°), northeast (NE, 45°), and southwest (SW, 270°). This approach ensured representative coverage of the area, while accounting for local wind-driven influences on plastic deposition.

Sampling procedures were carefully designed to account for local wind conditions and minimise contamination risks. Following the collection, all samples were meticulously preserved to prevent contamination and subsequently transported to the Water Quality Laboratory of Çanakkale Onsekiz Mart University (Türkiye) for analysis.

Plastic Isolation

In the laboratory, samples were sieved using a 1.00 mm mesh stainless steel sieve to remove fine sediments. The retained fraction was transferred to metal trays, where tap water was added, and the mixture was left undisturbed for 48 h. This settling period allowed buoyant plastic particles to separate based on their lower specific gravity. Floating particles were retrieved using sterilised forceps, transferred to Petri dishes, and air-dried in a controlled environment to prevent contamination. Particle colour and morphology were recorded under daylight conditions.

Plastic Measurement and Classification

Isolated plastic particles were distinguished based on density differences and individually measured using a scale board, with their dimensions systematically recorded. As no spectrometric analysis was conducted, only plastic particles larger than 2.00 mm, which are sufficient for visual identification according to Isobe et al. (2019), were included in the analysis. Additionally, the type and colour of each particle were documented during the measurement process.

Volume and Surface Area of Plastics

To quantify the dimensions of plastic particles, ImageJ version 1.54 g (Wayne Rasband and contributors, National Institutes of Health, Bethesda, MD, USA; http://imagej.org) software (Schneider et al., 2012) was used to obtain their major and minor axes, along with additional parameters such as angle (the orientation of the primary axis relative to a line parallel to the x-axis of the plastic particle image) and area (the projected surface area in square pixels, later converted into metric units). These parameters, particularly the area, were incorporated into the "equivalent spherical diameter" (ESD) formula to approximate the spherical volume of each particle (Colas et al., 2018). The ESD formula is defined as:

$$ESD = 2 \times \sqrt{\left(\frac{Area}{\pi}\right)} \quad (1)$$

ESD: represents the equivalent spherical diameter
Area: corresponds to the surface area of the plastic particle

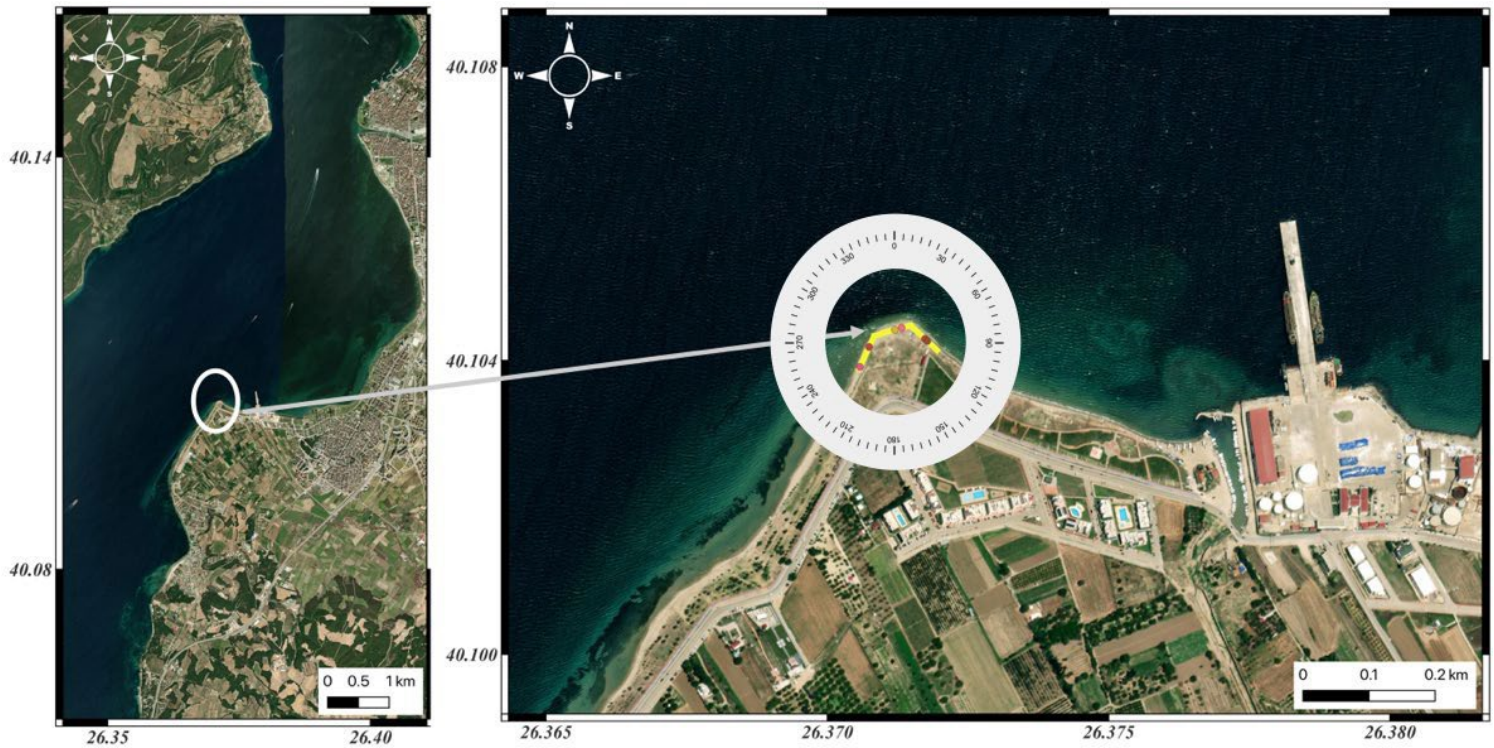

Figure 2. Illustration of the sampling area of Kepez Cape in the Çanakkale Strait, created by QGIS

Once the ESD of each particle was determined, its volume was calculated using the standard sphere volume formula. This approach provides a reasonable approximation of particle volume, despite the irregular morphologies of plastic particles, allowing for more consistent comparisons across samples.

Considering that two sampling points were selected along each 50-m transect, forming the three transects of 150 m in total, and plastic debris collected using 30 × 30 cm quadrats at each point, this will correspond to a total sampled area of 0.18 m² per transect (2 × 0.09 m²). Based on the quadrats at each sampling point, particle counts per surface area (items/cm2) have been calculated using the equation below:

$$\sum PC = \frac{item\#}{SA} \quad (2)$$

where,

∑PC: Total plastic count per area

item#: represents the number of plastic items

SA: corresponds to the sampled surface area

Statistical Analysis

To compare plastic pollution levels across the three directional coastal zone areas of the sampling stations, statistical analyses and data visualisations were carried out using R version 4.3.1 (R Core Team, 2023). The dataset comprised individual plastic particles collected from three coastal stations (NNE, NE, and SW), for which surface area (mm²) and volume (mm³) were measured. Prior to inferential testing, the Shapiro–Wilk test was applied to assess the normality of the distributions within each station. As the data significantly deviated from normality ($p<0.05$ in all cases), non-parametric tests were employed.

Differences in surface area and volume among stations were evaluated using the Kruskal–Wallis H test. Where significant effects were detected, pairwise comparisons were performed using Dunn's test with the Bonferroni correction to adjust for multiple comparisons. All tests were two-tailed, and results with $p<0.05$ were considered statistically significant.

Results and Discussion

Long-term meteorological records from the Çanakkale Strait indicate that the prevailing wind direction is north-northeast (NNE), followed by a secondary dominant wind from the northeast (NE). Further, a significant yet less frequent dominant wind is observed from the southwest (SW) (TSMS, 2012; Arslan et al., 2020).

A total of 74 plastic items were collected, specifically 32 from the NNE, 30 from the NE, and 12 from the SW. Surface area and volume were highest at NNE, followed by NE, with the lowest values obtained at SW (Table 1). These patterns suggest a higher deposition of larger debris along shorelines more directly exposed to Black Sea surface flows.

Table 1. Quantities, surface areas, and volumes of plastic particles were identified in the samples collected from different coastal zone locations in the Strait of Çanakkale

Station	Plastic particle (#)	Surface area (cm^2)[a]	Volume (cm^3)[b]
NNE	32	432.19	352.49
NE	30	411.75	747.24
SW	12	25.99	4.95
Total	74	869.94	1,104.69

[A, b] Surface area and volume of particles were dimensionally quantified using the Equivalent Spherical Diameter equation given as equation no 1. NNE: north-north-east, NE: north-east, SW: south-west

To contextualise these findings relative to sampling effort, surface area and volume were normalised per square meter. The NNE station exhibited the highest value of plastic counts (177.78#) for the surface area of 2400 cm², followed by NE (166.66#) with a coverage of 2280 cm², and SW (66.66#) with 140 cm² surface coverage, across a total sampled area (Table 2).

Table 2. Density-adjusted plastic particle metrics by stations (per cm²), selected along the coastal zone locations in the Strait of Çanakkale

Station	Particle count (#) *(items/cm²)*	Surface area (cm^2)*	Volume (cm^3)*
NNE	**177.78** ***(0.0741)***	**2400**	**1940**
NE	**166.66** ***(0.0731)***	**2280**	**4140**
SW	**66.66** ***(0.4761)***	**140**	**20**
∑SA	**411.1** ***(0.0851)***	**4820**	**6100**

* Surface area (SA) and volume of particles were dimensionally quantified using the Equivalent Spherical Diameter equation given as equation no 1. Particle counts per unit surface area (items/cm²) have been calculated using equation (2). NNE: north-north-east, NE: north-east, SW: south-west, $\sum_{SA}$ = total coverage of surface area

Kruskal-Wallis tests confirmed significant differences in surface area across stations ($p < 0.001$), with post-hoc analysis revealing that NNE had significantly higher values than NE. No significant difference was found between SW and the other stations.

The mean surface area per item was also greater at NE and NNE stations (1.3×10^{-3} m²/item) compared to SW stations (0.2×10^{-3} m²/item), suggesting that larger plastic fragments preferentially accumulate where Black Sea surface currents dominate. Conversely, the SW station, more influenced by Mediterranean inputs, retained smaller, more fragmented pieces of plastic (Figure 3). Surface area proved a more informative metric than particle counts. For instance, while NNE and NE had similar counts, NNE had nearly double the total volume, suggesting greater ecological impact due to larger debris size. These larger particles have greater potential to serve as vectors for invasive species, biofilm colonisation, and persistent organic pollutants (Zettler et al., 2013; Holmes et al., 2012). Moreover, surface area is a critical factor in the leaching behaviour of plastic additives such as bisphenol A and phthalates, which have known endocrine-disrupting properties (Hermabessiere et al., 2017).

When the Kruskal-Wallis test was conducted to assess the statistical difference in plastic surface area between sampling stations due to non-normality in the dataset, a significant difference was found among the three stations ($\chi^2 = 18.24$, df = 2, $p = 0.0001$), indicating that surface area values were not uniformly distributed across the study site. Post-hoc pairwise comparisons, using Dunn's test with the Bonferroni adjustment, provided further insight. Namely, a significant difference was found between the NNE and NE stations ($p = 0.00008$), while the difference between the SW and NE stations was marginally non-significant ($p = 0.06$). No significant difference was detected between the SW and NNE stations ($p = 1.0$).

These results highlight the NNE station as a central deposition zone, likely due to persistent wind exposure and alignment with south-westward currents. The minor elevation in surface area at SW compared to NE may reflect complex localised influences but lacks statistical support. Overall, the observed spatial variability supports the role of wind-driven transport and current directionality in shaping patterns of plastic accumulation along the coast (Figure 4).

Beyond quantitative metrics, particle morphology and colour were documented. Foam was the predominant type (51%), followed by fibre (43%), fragment (5%), and pellet (1%). The NE station showed the highest diversity of plastic types, whereas only foam, fibre, and fragments were noted in the NNE and SW stations.

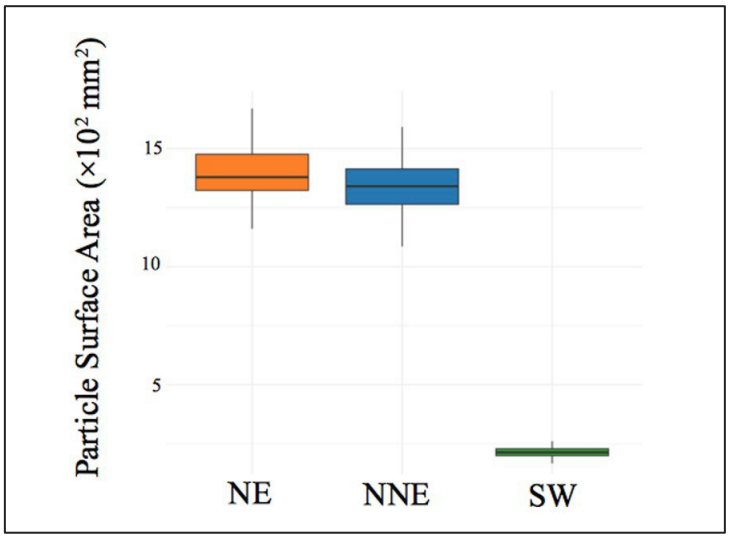

Figure 3. Distribution of individual plastic particle surface areas by station. NNE: north-north-east, NE: north-east, SW: south-west

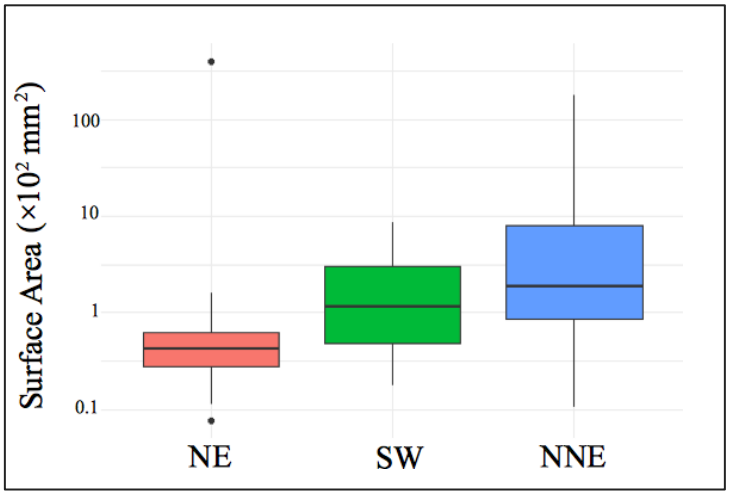

Figure 4. Total surface area of plastic debris collected from the three coastal stations of Kepez Cape, presented by station. NNE: north-north-east, NE: north-east, SW: south-west

Considering the colour properties found in the present study, white was the most common colour (38%), likely due to the use of titanium dioxide pigments, a compound widely used in the production of white plastics (Christie, 1998). The white colour was followed by green (26%) and grey (26%) at similar levels. The presence of green and grey fragments further reflects potential sources related to branding, packaging and fishing gear. Christie (1998) reported that green plastics are typically pigmented by using chromium (III) oxide (Cr_2O_3). Studies have shown that certain pigments contain heavy metals, including chromium (Cr), zinc (Zn), lead (Pb), cobalt (Co), titanium (Ti), and cadmium (Cd) (Campanale et al., 2020) which may be released into the environment during degradation (Christie, 1998), and particularly chromium (Cr), arsenic (As), mercury (Hg), cadmium (Cd), and lead (Pb) are reported as toxic and carcinogenic to both animals and human beings (Tchounwou et al., 2012), posing significant health concerns, particularly if absorbed into food webs or penetrating the sediment and groundwater systems.

The findings highlight the significant impact of wind and hydrodynamic forces on the transport and accumulation of plastic. The NNE station emerged as a depositional hotspot, potentially due to persistent wind exposure and alignment with Black Sea-derived surface currents. Similar dynamics have been observed in other transitional systems, such as the Strait of Gibraltar and the Istanbul Strait, where narrow topography and stratified flows enhance debris retention (Cózar et al., 2021; Isobe et al., 2019). This observation aligns with broader findings in marine environments, such as those reported in the Bay of Bengal, where plastic debris has also exhibited spatial and morphological variability in response to hydrodynamic forces (Mondal et al., 2024).

Like maritime traffic, winds play a significant role in transporting debris across coastal and marine environments. In recent decades, plastics, now the predominant component of marine litter, have also been shown to travel considerable distances under the influence of wind (Cózar et al., 2021), which is in agreement with findings in the present study, conducted along the Çanakkale Strait, a region characterised by its bi-directional strong wind regimes. The findings in this study highlight the importance of incorporating surface area as a key metric in assessing the environmental impact of coastal plastic pollution, offering a more nuanced understanding of transport mechanisms in complex marine systems. As recently underlined by Delaeter et al. (2022), additives such as phthalates and bisphenols, incorporated to enhance plastic properties during manufacturing, may leach over time into the marine environment, resulting in rates proportional to surface area (Delaeter et al., 2022). Therefore, surface area is a critical metric for understanding the impacts of plastic pollution on the water column and biota, as it governs interactions such as biofouling, contaminant adsorption, and the leaching of additives used in plastic production.

Addressing the targets for improving future work, this study highlights the importance of morphometric indicators, specifically surface area and volume, in evaluating the ecological significance of plastic debris accumulation. Building upon these findings, future work should aim to integrate morphometric data with spatial analysis tools such as Geographic Information Systems (GIS) and remote sensing. By georeferencing plastic deposition patterns and correlating them with wind, current, and shoreline morphology datasets, it will be possible to model plastic transport dynamics with greater precision.

The use of drone-based imagery and satellite-derived wind

and surface current data could enhance temporal monitoring and facilitate the detection of seasonal or event-driven variability in plastic accumulation. Such integration would allow for the creation of high-resolution spatial risk maps, which can inform local coastal management and policy-making.

Moreover, expanding this methodology to other regions of the Turkish Straits System and similar bidirectional marine corridors could help assess the generalizability of morphometric indicators in dynamic hydrodynamic contexts. Future studies may also incorporate machine learning algorithms for automated plastic classification and volumetric estimation from imagery, further improving data efficiency and standardisation in coastal plastic monitoring protocols.

Conclusion

This study demonstrates the value of incorporating morphometric parameters into assessments of plastic pollution. Surface area and volume provide a more ecologically meaningful understanding of pollution load than particle count alone. Wind-driven transport and current stratification have a significant influence on deposition patterns in narrow straits, such as the Çanakkale Strait. Results from the present study call for wind- and current-informed monitoring strategies and highlight the need to standardise morphometric measurements in coastal plastic surveys. Expanding this approach to other straits could enhance regional understanding of plastic dynamics across the Mediterranean basin. The conclusions drawn here are based strictly on the quantitative data collected during the study, thereby avoiding speculative interpretations.

Compliance with Ethical Standards

Conflict of interest: The author declares no actual, potential, or perceived conflict of interest for this article.

Ethics committee approval: No living organisms have been used in any part of this research; therefore, no ethics committee approval is required for this study.

Data availability: The data will be made available upon request from the author.

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Disclosure: -

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