

Posidonia oceanica wrack intercepts plastic debris: First evaluated evidence on Maltese beaches

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ABSTRACT

Plastic debris constitutes a major solid waste pollutant, endangering the marine ecosystem and contributing to sediment accumulation. The presence of plastics in *Posidonia oceanica* banquettes poses risks for organisms that rely on this habitat type for shelter and food. *P. oceanica* meadows offer vital ecosystem services, including habitat provision for marine organisms, oxygen production, CO₂ absorption, climate change mitigation, and seawater filtration. At the end of their life cycle, leaves from this seagrass dislodge and accumulate on shorelines as seagrass 'banquettes', i.e. wrack. Inasmuch, *P. oceanica* banquettes on Mediterranean beaches may serve as indicators for plastic debris pollution in the coastal ecosystem. This study for the first time quantified and evaluated the abundance of plastic debris intercepted by the deposits of *P. oceanica* banquettes on three Maltese beaches at Qalet Marku, Xemxija, and Ramla tal-Qortin. The highest volume of beached *P. oceanica* wrack was recorded at Qalet Marku (730.71 m³), which included a mean content of plastic items at 24.75 items/m². At Xemxija, the mean content of plastic items was 102.42 items/m², while the mean content at Ramla tal-Qortin was 32.25 items/m². Therefore, the most polluted beach in terms of plastic pollution was Xemxija, where a high level of anthropogenic activities was noted in the vicinity of the beach. The present study provides a baseline for macro (>25 mm)-, meso (5–25 mm)-, and micro (<5 mm)-plastics trapped within the banquettes of *P. oceanica* on Maltese beaches.

1. Introduction

Annually, a substantial quantity of plastic waste amounting to hundreds of thousands of metric tonnes, is discharged into the marine ecosystem, either via direct or indirect means. This has a harmful effect on the natural habitats of marine organisms, both in the open ocean and on the seabed (Seggiani et al., 2017). Despite its small surface area of only 0.7 % of the whole ocean, the Mediterranean Sea supports a high diversity of marine life that includes 7.5 % of the global marine fauna and 18 % of marine flora. This semi-enclosed basin has several islands, and its underwater ecosystems play a crucial role in supporting migratory, feeding, and reproductive activities for several species (Geoff and

Nikolay, 2022). However, recent data indicate that the Mediterranean Sea has the sixth-highest concentration and accumulation of marine waste material, including plastic debris, worldwide (Expósito et al., 2021; Pietrelli et al., 2017). Approximately 80 % of the plastic waste originates from terrestrial sources (Andrady, 2017) including agriculture, personal care goods, textiles, tourism, plastic manufacturing, and road transport (Stothra et al., 2021). Approximately 10–20 % of plastic debris originate from marine sources, including commercial fishing, seaside tourism, marine vessels, and offshore industries (Karbalaei et al., 2019; Li, 2018). The MSFD GES Technical Subgroup on Marine Litter (MSFD-GES, 2011) has recently proposed a standardised classification system for plastic debris based on size. According to this classification,

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debris larger than 25 mm is classified as macroplastics, debris ranging from 5 to 25 mm is classified as mesoplastics and debris measuring from 1 μm to 5 mm is classified as microplastics.

P. oceanica (Linnaeus) Delile, 1813 is designated as a protected species according to several international agreements approved by Mediterranean nations. It is also considered a crucial natural environment that requires conservation efforts, as outlined in the Habitat Directive (92/43/EEC). This directive recognises *P. oceanica* beds as priority habitats (Habitat Type 1120: *P. oceanica* beds - *Posidonia oceanica*). In addition, *P. oceanica* has been chosen as a benchmark for assessing the Good Environmental Status of maritime regions under the Maritime Strategy Framework Directive (MSFD, 2008/56/EC) (Telesca et al., 2015). *Posidonia oceanica* undergoes leaf abscission during the autumn season. Subsequently, propelled by the forces of waves and currents, the loose leaves eventually gather on nearby beaches to form wrack beds (dead seagrass material), also known as *Posidonia* banquettes (Sanchez-Vidal et al., 2021), which can be present in substantial amounts. The Maltese Islands conform to this pattern, as also reported by the Malta Tourism Authority (MTA), which directs regular grooming of 53 coastal sites on the main island of Malta and of over 15 sites on the island of Gozo. Each year, approximately 19,000 tonnes of waste, which includes seagrass wrack is removed (Portugal et al., 2009). Removing the seagrass wrack can be considered to be ecologically disruptive because these vegetative deposits contribute to the stability of the flora of sand dunes, while also providing protection to the coastline, decreasing coastal erosion, and dampening waves (Cantasano, 2021). *Posidonia* banquettes prevent desiccation of the soft substratum and provide essential nutrients to the dune vegetation (Del Vecchio et al., 2013). In addition, removal of the seagrass wrack involves using heavy machinery, which can significantly impact the shoreline and contribute to Greenhouse Gas emissions due to fuel consumption by the equipment used (Leemans et al., 2021). On the other hand, small invertebrates and other organisms that interact with the banquettes may inadvertently ingest microplastics, leading to harmful effects that can propagate through the food web (Awuchi and Awuchi, 2019). Furthermore, since plastics can slow down the breakdown of organic material, they may change the natural decomposition rates of banquettes. This could have an impact on habitat dynamics and nutrient cycling (Farooqi et al., 2021).

Seagrass wrack may also exert negative effects on the environment (Hyndes et al., 2022). Microbial decomposition of seagrass wrack can result in the release of considerable quantities of greenhouse gas emissions, including carbon dioxide (CO_2) and methane (CH_4), into the atmosphere, worsening climate change (Leemans et al., 2021). For instance, research by Coupland et al. (2007) indicates that seagrass wrack found on Australian beaches emits carbon dioxide (CO_2) at a rate of $6 \mu\text{mol m}^{-2} \text{s}^{-1}$. Furthermore, a study by Misson et al. (2021) revealed that the decomposition of seagrass wrack also results in methane (CH_4) emissions, with the amount released being influenced by factors such as salinity and environmental temperature. Globally, the annual CO_2 -C flux of seagrass wrack is estimated to range between 1.31 and 19.04 Tg C yr^{-1} (Liu et al., 2019). Notably, seagrass wrack exposed to continuous wetting in the intertidal zone has up to 72 % more greenhouse gas emissions compared to seagrass wrack high up the beach with less exposure to moisture (Liu et al., 2019).

Anthropogenic debris such as plastics may be present in beach wrack (Poeta et al., 2016); plastics have been found in wrack made up of dead material of several species of plants, including seagrasses from the genera *Halodule*, *Syringodium*, *Thalassodendron*, *Zostera*, *Heterozostera*, *Amphibolis*, and *Cymodoce* (Menicagli et al., 2021; Ciaralli et al., 2024). *P. oceanica* banquettes may serve as indicators of plastic debris pollution in the coastal ecosystem (Sanchez-Vidal et al., 2021; Alomar et al., 2024). The present study represents the first quantification of plastic debris trapped within *P. oceanica* banquettes on Maltese beaches. The objectives of the study were to: (i) evaluate the abundance and composition of plastic debris present within the *P. oceanica* wrack; (ii)

explore the influence of anthropogenic pressure on plastic abundance (iii) assess the potential correlation between the volume of *P. oceanica* wrack and abundance of plastic in the seagrass material.

2. Materials and methods

2.1. Study area

The Maltese Islands, however little in size at 316 km^2 , boast a reasonably lengthy coastline measuring 272 km (Axiak et al., 1999). Most of the coastline, around 90.5 %, consists of rocky shoreline. Sandy and shingle coasts make up a combined 2.4 % of the coastline, while the remaining 7 % is developed or built up. Both shingle and sandy beaches periodically receive deposits of seagrass wrack, primarily consisting of *P. oceanica* dead seagrass material. Approximately 60 % of the coastline of Malta is not accessible, resulting in significant human-induced pressures on the remaining accessible shoreline due to the Island's high population density (1194 km^{-2}) and the massive influx of tourists (Deidun et al., 2005). The three beaches studied include (i) Qalet Marku ($35^\circ 56' 35.26'' \text{N}$; $14^\circ 27' 00.99'' \text{E}$); (ii) Xemxija ($35^\circ 56' 47.18'' \text{N}$; $14^\circ 22' 59.93'' \text{E}$); and (iii) Ramla tal-Qortin ($35^\circ 59' 11.92'' \text{N}$; $14^\circ 21' 04.11'' \text{E}$) (Fig. 1). All three are ungroomed beaches and relatively small, being around 10 m long, measured from the shoreline.

2.2. Sampling

The volume of *P. oceanica* banquettes occupying each beach was evaluated by using the following formula: volume = length x width x depth.

Based on the level of exposure to prevalent anthropogenic disturbances observed during sampling, the beaches were classified as high, medium, or low. The observed human activities and disturbance included the presence of restaurants, bars, hotels, shops, developed backshore, busy roads, moored boats, and the presence of boathouses. During April and May 2024, *P. oceanica* wrack was sampled using a 1 m^2 quadrat to a depth of 20 cm along transects that were 9 m long and laid perpendicular to the foreshore (Fig. 2). Samples were collected at distances of 0 m, 2.5 m, and 7 m (referred to as stations in this study) from the shoreline (Sanchez-Vidal et al., 2021). Each transect was around 1 m wide. To obtain a representative sample from each beach, two transects, separated by 20 m, were laid at each study site (Fig. 2). Along each transect, suspected plastic items that were present within the quadrat which was placed on both sides of the sampling line, starting uniformly from the surface to the maximum depth of 20 cm, were collected and placed in a labelled container. Sub-samples of *P. oceanica* wrack within each quadrat were also collected to fill a 5 L container. The weight of the



Fig. 1. Map of Maltese Island showing the study sites.

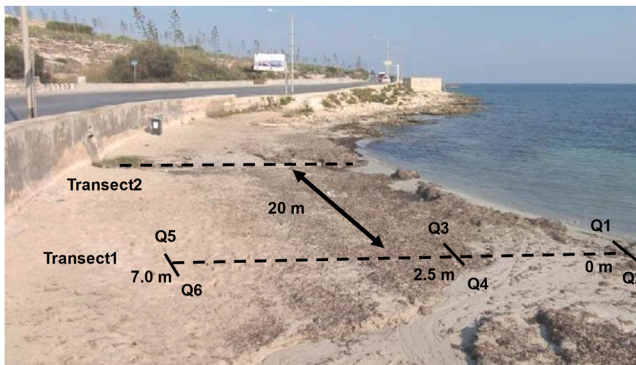


Fig. 2. A graphical illustration of transect line and sampling stations.

P. oceanica wrack material in such a container weighed around (740 – 1470 g). 12 replicate quadrats with plastic items and 12 sub-samples of *Posidonia* wrack material from the 12 quadrats were therefore collected from each study site. Once collected, the samples were transported to the laboratory for further analysis

2.3. Plastic isolation and identification

Following the procedure of Sanchez-Vidal et al. (2021). Once in the laboratory, the samples of *P. oceanica* wrack were dried at room temperature and low humidity for several days. The samples were then disentangled and sieved using stainless steel sieves with sizes 4 mm, 2 mm, and 1 mm; the contents were emptied in small fractions into different aluminium trays. Suspected plastics were identified by the naked eye with a minimum detectable size of 500 μm (0.5 mm) by an experienced observer and picked up using forceps (Lacerda et al., 2019). Items were thereafter added to those collected on the field from the same quadrats. According to the literature (Abby, 2018; Beckingham et al., 2023), for each suspected item, the following techniques were used to confirm their plastic nature: (i) prodding pieces (most plastic items are quite flexible and will not break when prodded. When poked with a tweezer, plastic items frequently bounce or spring. Those pieces that break when touched are not considered plastic unless they pass the hot needle test.) and (ii) the hot needle test (suspected plastic items were tested with a heated soldering iron, fiber “passes” when it either melts or bends/curles while fiber “fails” when there is no response, charring/-burning). The identified plastic items were quantified and measured over their largest cross-section using a ruler (Lacerda et al., 2019). This study specifically focused on microplastics within the size range of 1–5 mm (Lee et al., 2013). We categorised the plastic items into three distinct size categories: microplastics (1–5 mm - large microplastics), mesoplastics (5–25 mm), and macroplastics (>25 mm). They were further classified based on their form/shape and colour. The total plastic items in each quadrat were weighed using a weighing balance.

2.4. Statistical analysis

Descriptive analyses including graphs were carried out using Microsoft Excel version 2405. Crosstab analysis of shape distribution across the sites was performed using SPSS statistical software. The one-way analysis of variance (ANOVA) was used to test for significant differences in plastic size and shape across the sites. Pearson’s Product Moment Correlation was used to determine the correlation between the volume of *Posidonia* banquettes and plastic abundance. All values were deemed statistically significant when $p \leq 0.05$. Inferential statistical analyses were done in SPSS statistical software (Sokal and Rohlf, 1987).

We used a Pearson’s Product-Moment Correlation analysis, to explore any statistical relationship between the macroplastic, mesoplastic, and microplastic abundances at the three study locations. Even though Pearson’s correlation coefficient is a commonly used statistical

metric to evaluate the linear relationship between two continuous variables (Field Ssage, 2024), this study cautiously utilized this statistical method because the sample size for this study was limited to three observations (three sites) ($N = 3$). Hence, the incredibly small number of degrees of freedom ($df = 1$) precludes both statistical significance testing and valid inference (Bonett and Wright, 2000). The correlation coefficients are thus presented solely for exploratory insight into potential patterns that may warrant further investigation with a larger sample. Small sample sizes can lead to unstable and potentially misleading correlation values, particularly in environmental datasets where variability is often high and relationships can be nonlinear (Wilcox, 2009). This approach aligns with exploratory data analysis principles, which advocate transparency in early-stage findings.

3. Results

The volume of *P. oceanica* banquettes recorded at Qalet Marku, Xemxija, and Ramla tal-Qortin, was 730.71 m^3 , 542.24 m^3 , and 497.85 m^3 , respectively. Therefore, the beach with the highest volume of seagrass wrack was Qalet Marku, followed by Xemxija and Ramla tal-Qortin.

The beaches were classified according to the degree of exposure to anthropogenic disturbances or activities in the area as follows: (i) Highly exposed – Xemxija, (ii) Medium – Ramla tal-Qortin, (iii) Low - Qalet Marku. Xemxija Beach was particularly characterized by the presence of several restaurants, bars, hotels, shops, buildings, busy roads, and several boats moored in the bay. Ramla tal-Qortin had several boat-houses on the backshore of the bay’s headlands. Qalet Marku had a pristine coastline with no obvious disturbances, with the presence of a few mobile caravans on either side of the beach.

3.1. Plastic abundance and size classification

A total of 1913 plastic items were found across the three investigated sites, with the seagrass banquette at Xemxija having the highest number of plastic items (1229), followed by Ramla tal-Qortin (387) and Qalet Marku (297) (Table 1). The abundance of plastics at the Qalet Marku sampling stations ranged from 36 – 64 items/ m^2 , with a mean abundance of 24.75 items/ m^2 . At Xemxija, the amount of plastic items at the sampling stations ranged from 121 – 267 items/ m^2 , with a mean abundance of 102.42 items/ m^2 . The amount of plastic items at the Ramla tal-Qortin sampling stations ranged from 15 – 139 items/ m^2 , with a mean abundance was 32.25 items/ m^2 . The total weight per quadrat of plastic items in Qalet Marku ranged from 0.15 g – 44.33 g, with a mean weight of 9.87 g. At Xemxija the total weight per quadrat ranged from 9.73 g – 111.6 g, with a mean weight of 38.66 g. The total weight per quadrat at Ramla tal-Qortin ranged from 0.31 g – 64.13 g, with a mean weight of 15.80 g. Plastic items were classified based on size as follows: (i) at Qalet Marku, 73 (24.6 %) were microplastics, 128 (43.1 %) were

Table 1

Results of Pearson’s Product-Moment Correlation analysis on the statistical relationship between macroplastics, mesoplastics, and microplastics abundances at the three studied locations.

Correlations		MACRO	MESO	MICRO
MACRO	Pearson Correlation	1	.998*	.995
	Sig. (2-tailed)		.035	.064
	N	3	3	3
MESO	Pearson Correlation	.998*	1	.988
	Sig. (2-tailed)	.035		.099
	N	3	3	3
MICRO	Pearson Correlation	.995	.988	1
	Sig. (2-tailed)	.064	.099	
	N	3	3	3

* . Correlation is significant at the 0.05 level (2-tailed).

mesoplastics, and 96 (32.3 %) were macroplastics; (ii) at Xemxija, 167 (13.6 %) were microplastics, 650 (52.9 %) were mesoplastics, and 412 (33.5 %) were macroplastics; (iii) at Ramla tal-Qortin, 71 (18.4 %) were microplastics, 170 (43.9 %) were mesoplastics, and 146 (37.7 %) were macroplastics. Mesoplastic was the most abundant size of plastic items in all analysed banquettes (Fig. 3). The ANOVA indicated a significant difference ($p < 0.05$) in the size of plastic items across the three study sites.

The result of the Pearson correlation showed a significant, strong and positive correlation ($r = 0.998$, $p < 0.05$) between the abundance of macroplastics and mesoplastics across the three sampling sites. It also showed a strong positive relationship ($r = 0.995$) between the abundance of macroplastics and microplastics, although the relationship is not statistically significant ($p = 0.064 > 0.05$). Similarly, there was a strong positive relationship ($r = 0.988$) between the abundance of mesoplastics and microplastics across the three sites, although the relationship was not statistically significant ($p = 0.099 > 0.05$) (Table 1).

3.2. Shape and colour composition of plastic items

The results of crosstab analysis indicating the distribution of shape/form of the plastic items recorded from the seagrass banquettes across the three study sites are given in Tables 2, 3 and 4. In Qalet Marku, the fragments was the dominant shape (177) followed by films (65). In Xemxija fragments (396) was also the dominant shape, followed by film (390) and foam (159). In Ramla tal-Qortin, fragment was also the dominant shape (217), followed by film (57) and other shapes/forms, including filament (26). Fragment was the dominant shape across the three investigated sites, with 790 plastic items out of the total 1913 plastic items found across the three sites, followed by film. The ANOVA indicated a significant difference ($p < 0.05$) in the shape of plastic items across the three study sites. According to Fig. 4, 13 colours were identified for the reported plastic items were identified in a total of 13 colours, with white as the dominant one across the three studied beaches, with a total of 730 plastic items. Blue was the second dominant colour at Qalet Marku and Ramla tal-Qortin, while at Xemxija transparent was the second dominant colour.

4. Discussion

4.1. Plastic abundance and size classification

This study presents the first recorded evidence of plastic items trapped within *P. oceanica* banquettes on Maltese beaches. Results

Table 2

Crosstab analysis of shape distribution in Xemxija beach.

Xemxija		Size Classification			Total
		Microplastics	Mesoplastics	Macroplastics	
Shape/ Form	Fragment	48	155	193	396
	Filament	1	34	56	91
	Film	11	150	229	390
	Pieces of Nets	0	21	76	97
	Foam	105	44	10	159
	Cap	0	0	4	4
	Pellet	2	0	0	2
	Tape	0	0	11	11
	Cable tie	0	0	15	15
	Mini spoon	0	0	11	11
	Fishing line	0	0	23	23
	Cigarette butt	0	1	3	4
	Shotgun cartridge	0	0	1	1
	Seal/linear	0	3	2	5
	Rope	0	1	6	7
	Plant pot	0	0	1	1
	Button	0	2	0	2
	Food container	0	0	1	1
	Cup	0	0	1	1
	Cosmetics bottle	0	0	1	1
	Cap ring	0	0	1	1
	Stirrer	0	0	1	1
	Egi	0	0	1	1
	Bag	0	0	1	1
	Mini fork	0	0	1	1
	Wire covering	0	0	1	1
	Bread clip	0	1	0	1
Total		167	412	650	1229

showed a mean plastic items concentration of 24.75 items/m², 102.42 items/m², and 32.25 items/m² at Qalet Marku, Xemxija, and Ramla tal-Qortin banquettes, respectively, with a total of 1913 plastic items isolated from the three study sites. Mesoplastics (49.6 %) were the most abundant plastic debris found at the three study sites, this corresponds to the results obtained by Zhang et al. (2020) that reported mesoplastics (44.4 %) as the most abundant in all stations in their study. Findings from the present study have confirmed that *P. oceanica* wrack can trap significant amounts of plastic debris. This agrees with a previous study reporting the presence of plastic debris in 50 % of the investigated *Posidonia* wrack (Sanchez-Vidal et al., 2021). Such a finding is very

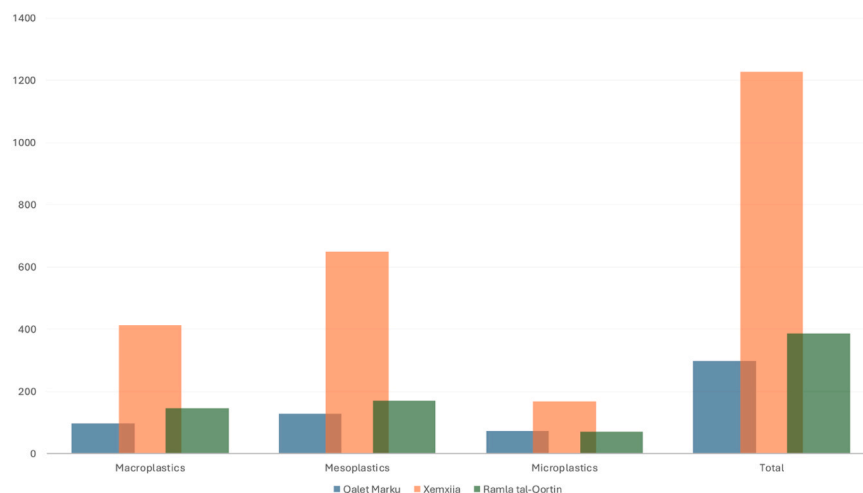


Fig. 3. Number of plastic items divided in Macro-, Meso- and Microplastics, and their total amount (Total), for the three analysed sampling sites.

Table 3
Crosstab analysis of shape distribution in Qalet Marku beach.

Qalet Marku		Size Classification			Total
		Microplastics	Mesoplastics	Macroplastics	
Shape/ Form	Fragment	44	84	49	177
	Bottle	0	0	1	1
	Lid	0	1	0	1
	Filament	2	2	8	12
	Film	10	34	21	65
	Pieces of Nets	0	0	11	11
	Foam	12	4	2	18
	Cap	0	1	2	3
	Glove	0	0	1	1
	Pellet	5	2	0	7
	Tape	0	0	1	1
	Total	73	128	96	297

concerning, given the rate of decline that seagrasses are presently experiencing worldwide, equivalent to or even greater than those of rainforests and coral reefs, with estimates indicating an unprecedented

worldwide loss rate of around 7 % per year (Waycott et al., 2009). The primary cause of seagrass decline is predominantly inadequate water quality stemming from coastal expansion, subpar land management practices, physical degradation, and ecological alteration due to over-exploitation of fisheries (Cullen-Unsworth and Unsworth, 2013). However, plastic waste may create serious problems for seagrasses all over the world (Sanchez-Vidal et al., 2021), adding to the already-present negative impacts, including ones resulting from climate change, the spread of invasive species, shoreline erosion, and mechanical impacts (Marbà et al., 2014; Orth et al., 2006), ultimately leading to fragmentation of seagrass meadows and a consequent adverse impact on the ecological services they provide.

4.2. Shape and colour composition of plastic items

Results from the crosstab analysis of shape distribution showed that the common shapes/forms present in all the analysed banquettes were fragments, filaments, film, pieces of nets, foam, caps, pellets, and tape (Table 2). Other shapes or forms were not present in all three sites, such as cable ties (found at Xemxija and Ramal tal-Qortin but absent at Qalet

Table 4
Crosstab analysis of shape distribution in Ramla tal-Qortin beach.

Ramla tal-Qortin		Size Classification			Total
		Microplastics	Mesoplastics	Macroplastics	
Shape/Form	Fragment	42	115	60	217
	Lid	0	2	1	3
	Filament	1	11	14	26
	Film	9	23	25	57
	Pieces of Nets	0	5	14	19
	Foam	9	9	0	18
	Cap	0	0	6	6
	Pellet	10	0	0	10
	Tape	0	0	3	3
	Cable tie	0	1	6	7
	Mini spoon	0	0	1	1
	Fishing line	0	0	7	7
	Cigarette butt	0	1	0	1
	Shotgun cartridge	0	0	1	1
	Seal/linear	0	2	2	4
	Rope	0	0	1	1
	Food container	0	0	1	1
	Seasoning pack	0	0	1	1
	Artificial flower	0	0	1	1
	Hair band	0	1	0	1
	Pharmaceutical blister pack	0	0	1	1
	Mini container	0	0	1	1
	Total	71	170	146	387

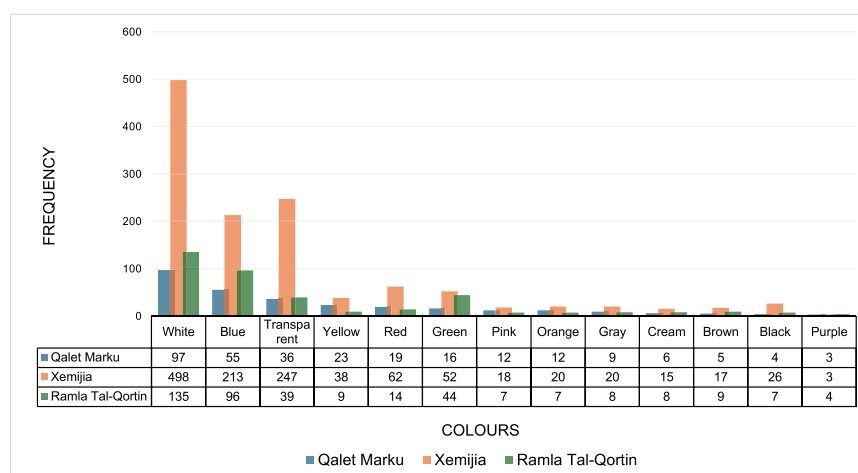


Fig. 4. Colour distribution of plastic items across the three study sites.

Marku) and gloves (found in Qalet Marku but absent in Xemxija and Ramla tal-Qortin). Fragment was the dominant shape across sites (41.3 %). This finding is in line with the literature, wherein fragments were reported as the dominant shape (61.29 %) in plastic items collected from *Posidonia* wrack (Sanchez-Vidal et al., 2021). Another study by Zhang et al. (2020) recorded fragmented plastic debris as the dominant shape (76.2 %). Concerning the colour of the isolated plastic items, the present study confirmed white as the dominant colour across the three investigated sites (38.2 %), with all 13 identified plastic item colours being widely present across the three study sites. Regarding marine sources of plastic pollution, results showed a predominant presence of fishing lines and ropes at Xemxija and Ramla tal-Qortin, pieces of fishing nets were present at the three study sites, and egi was present at Xemxija. Fishing, indeed, appears to be the leading cause of marine plastic pollution, as also indicated in the literature (Richardson et al., 2019; UNEP, 2016). Abandoned, lost, or discarded fishing gear has been acknowledged as a significant issue (FAO, 2018), with fishing ropes, nets, and lines representing significant contributors to the accumulation of fishing trash on beaches. Beached fishing debris might potentially discharge a significant amount of microplastic fragments, estimated to be about hundreds per metre (Wright et al., 2021).

The predominance of mesoplastics (5 – 25 mm) in this study signals a significant role for secondary sources, where plastics deteriorate over time through physical, chemical, and biological processes, influencing the local pollution landscape (Rangel-Buitrago et al., 2024). Also, the prevalence of fragments as the most common shape supports this perception, as these are often the result of weathering larger, rigid plastic objects like containers, packaging, and consumer goods. This pattern suggests that a considerable portion of plastic pollution consists not of newly introduced microplastics but rather of byproducts from long-standing, unmanaged plastic waste that has fragmented over time (Dey et al., 2024). It highlights the importance of addressing land-based sources, such as urban runoff, littering, and ineffective waste disposal, which are likely major contributors. Moreover, the dominance of mesoplastics points to coastal areas affected by wave action, sunlight exposure, and mechanical abrasion such as rocky shores and high-energy beaches, as key locations for plastic breakdown (Udugama et al., 2025; Gregory, 2009). Recognizing these trends in shape and size is crucial for guiding effective mitigation strategies, as it emphasizes the need to reduce the influx of large plastic items into the environment and enhance waste management infrastructure in coastal regions (Kibria et al., 2023; Kumar et al., 2021).

4.3. Comparison of the volume of *P. oceanica* banquettes and plastic abundance

The beach with the highest banquette volume was Qalet Marku (730.71 m³) followed by Xemxija (542.24 m³) and Ramla tal-Qortin (497.85 m³). The Pearson correlation coefficient ($r = -0.418$) indicated a weak negative correlation between the volume of *P. oceanica* banquette and plastic abundance; however, the p-value (0.726) indicated that the observed correlation was not statistically significant. This implies that the volume of *Posidonia* banquettes may not directly impact the abundance of plastic debris at the investigated sites. The weak linkage highlights the complexity and interplay of various environmental and human-caused factors. Intuitively, one might assume that larger volumes of wrack would correlate with increased plastic entrapment. However, actual accumulation is influenced far more significantly by external variables, such as the proximity to urban infrastructures and the intensity of human activity along the shorelines (Menicagli et al., 2022). Coastal areas situated near bustling urban centres, busy harbours, or popular tourist destinations frequently bear the brunt of plastic pollution, a consequence of inadequate waste management systems, runoff from rainwater, and the recreational activities of beachgoers (Alomar et al., 2024). This reality persists regardless of how much wrack is present on the beach.

Furthermore, hydrodynamic factors such as prevailing currents and ebb, and the dynamic movement of waves play a critical role in the transportation and deposition of plastic waste (Kumar et al., 2021). For example, regions that are sheltered by natural coastal formations or that experience onshore currents may trap and accumulate plastics more effectively, leading to striking concentrations of debris, even in areas with relatively low volumes of wrack (Menicagli et al., 2022). In contrast, open or exposed beaches may showcase impressive layers of wrack yet contain minimal plastic content due to the constant movement and dispersal of floating objects by the ocean's currents (Hyndes et al., 2022). This intricate tapestry of interactions underscores the urgent need for pollution monitoring methodologies that consider the diverse and interconnected variables at play, rather than relying solely on wrack volume as a singular indicator of plastic pollution levels (Martins et al., 2024).

4.4. Anthropogenic pressure and plastic abundance

Xemxija Beach was classified as heavily subjected to anthropogenic pressure, due to the high levels of human activities affecting the area. This was also confirmed by the number and abundance of isolated plastic items (the highest among the analysed banquettes), which confirmed the site as the most polluted out of all the three investigated beaches. Xemxija Beach constitutes a portion of the inner parts of Saint Paul's Bay; this bay is surrounded by restaurants, bars, hotels, shops, buildings, busy roads, and the presence of numerous moored boats. The bay has an area of around 14.53 km², and the population density is about 2205/km² (NSO Malta, 2022). Because Xemxija is an ungroomed beach, it is less attractive to local people and tourists. However, it still receives a few visitors. The high level of anthropogenic activities in this area does have an adverse impact, as highlighted by the highest abundance of plastic items trapped within the *Posidonia* wrack on this beach. Ramla tal-Qortin was classified as having medium-level exposure. This inlet has a surface area of about 22.64 km² and a population density of about 562.6/km² (NSO Malta, 2022). It had several boathouses on the backshore of the bay's headlands. Ramla tal-Qortin is popular amongst locals, especially those who own boathouses in the area. This inlet tends to be crowded on weekends from July to early September. Activities associated with the boathouses may be contributing to pollution on the beach, as shown by the presence of moderate amounts of litter on the beach, with an abundance of plastic items lower than those reported at Xemxija Beach. Qalet Marku was classified as having low-level exposure. The beach is located on a relatively pristine coastline, with a low level of disturbance, as also indicated by the present results, which showed the lowest abundance of plastic items at this site. The few mobile caravans around the beach are mostly used during the summertime by locals, with the beach rarely receiving visitors due to its ungroomed state.

Results from the present study indicate that anthropogenic activities, especially from land-based sources, can influence plastic abundance in coastal environments. Land-based sources are known to account for over 80 % of anthropogenic marine plastic trash worldwide (Jambeck et al., 2015; van Gool et al., 2021). On land, the most significant sources of larger plastic objects are construction materials, household products, packaging items, food and drink packaging waste, and waste generated from shipbuilding (Čulin and Bielić, 2016; Alomar et al., 2016). Microplastic discharge into the aquatic environment might likely come from sewage sludge and industrial operations, especially those involving granules and small resin pellets (Rolsky et al., 2020; Hale et al., 2020). Some of these items have been identified in the present study, confirming that beaches can accumulate macroplastics and microplastics globally (Asensio-Montesinos et al., 2019; Aslam et al., 2020; Browne et al., 2011). The increasing impacts of human activities and natural tidal variation are affecting marine beaches, which are the primary areas where land-based plastic debris reaches coastal waters (Delvalle de Borrero et al., 2020; Lee et al., 2015; Ivar do Sul and Costa, 2014).

Several studies have examined the spatial distribution and prevalence of human-made plastic waste on beaches and in marine ecosystems, such as estuaries, recreational beaches, and those that are heavily impacted by human activities (Cheung et al., 2016; Gao et al., 2021; Hengstmann et al., 2017). Monitoring of global plastic debris on beaches is essential for the determination of the quantity, composition, and sources of plastic debris (Hong et al., 2014; Nachite et al., 2019; Serra-Gonçalves et al., 2019).

4.5. Implications of plastic retention by seagrass wrack on waste management, policies, and pollution hotspots

The present study has shown that seagrass wrack can capture and store significant amounts of plastic debris, including microplastics. This phenomenon has important implications for coastal waste management practices and environmental policy (Li et al., 2023). Understanding how plastic builds up in coastal ecosystems like seagrass wrack is essential for developing effective and adaptive management strategies in response to the ongoing issue of plastic pollution. From a waste management perspective, the presence of plastic in seagrass wrack presents both challenges and opportunities (Mainardis et al., 2021). On one hand, wrack laden with plastic complicates beach cleanup efforts, as traditional cleanup initiatives often remove wrack indiscriminately, which can disrupt critical biological processes like nitrogen cycling and habitat provision (Hyndes et al., 2022). On the other hand, if managed carefully, these wrack zones can serve as effective mechanisms for intercepting plastic waste before it spreads into marine environments. This characteristic allows wrack zones to act as natural filters, concentrating plastic waste in more manageable areas and potentially simplifying waste removal efforts (Hyndes et al., 2022; Mainardis et al., 2021). This insight could lead to more focused cleanups and better resource distribution, enhancing the efficiency of coastal waste management while maintaining ecological sensitivity.

The presence of plastic in seagrass wrack calls for a re-evaluation of current waste management strategies (Rangel-Buitrago et al., 2024). Many existing policies focus primarily on terrestrial waste streams or direct marine inputs like fishing gear, often overlooking the role of coastal vegetation in absorbing and redistributing plastic debris (Kumar et al., 2021). Incorporating the ecological functions of seagrass wrack into waste management systems, regulations can be adjusted to promote environmentally sustainable waste disposal methods. For instance, guidelines could recommend seasonal or selective removal of wrack based on assessments of ecological sensitivity and plastic load, thereby minimizing disruptions to local biodiversity while addressing pollution concerns (Rangel-Buitrago et al., 2024). Additionally, monitoring plastic accumulation in seagrass wrack can serve as an effective tool for identifying marine pollution hotspots. Since seagrass meadows and wrack zones are often located in depositional habitats, they can provide valuable insights into adjacent water quality and pollution trends. Tracking changes in plastic deposition over time can reveal shifts in upstream waste discharge patterns, the effectiveness of stormwater runoff management, or instances of illegal dumping (Hyndes et al., 2022).

5. Conclusion

The present study provides the first evidence of macro-, meso-, and micro-plastics trapped within banquettes of *P. oceanica* on Maltese beaches. In this study, the volume of *P. oceanica* banquettes did not show a statistically significant impact on the abundance of plastic items present within the seagrass wrack. Conversely, anthropogenic activities around the beach may have a huge influence on the abundance of plastic debris found within the *P. oceanica* wrack that is accumulated on a beach. The removal of seagrass wrack due to recreational purposes on beaches can be deemed ecologically detrimental given their role in providing habitat and refuges for the associated biodiversity,

contributing to the dune formation, facilitating the colonization by psammophilous vegetation, protecting coastlines, reducing coastal erosion, and mitigating wave intensity. Moreover, the accumulation of plastics trapped within this seagrass wrack can considerably contribute to the degradation of this sensitive habitat, impacting all the essential associated ecosystems services. Adequate measures must therefore be employed to prevent the removal of *P. oceanica* banquettes from the beaches. Sustainable management procedures for *Posidonia* banquettes need to transition beyond mere beach trash removal to continuing maintenance. Therefore, we suggest that seagrass banquettes should be promoted to tourists as an important natural element of the beach and constitute support for a 'bio-beach'. To reach this goal it is essential to develop actions able to increase the awareness of different stakeholders (as local administrations, managers, beach users) on the importance of banquettes. This can be carried out by developing projects focused on increase the knowledge of beach users on the ecological role and the environmental relevance of these habitats, such as also providing management information to local administration and managers that can give an alternative to the banquettes' removal (i.e., displacement of wracks, burial of small banquettes during summer season to effectively remove them from sight by tourists) (Scarpato et al., 2020; Rotini et al., 2020). These practices can change the perspective of beach users, encouraging them to embrace the natural elements within the beach, looking to them as a resource more than a discomfort. Finally, new studies are needed to better understand the dynamics of *P. oceanica* banquettes at beaches in Malta, including their ability to trap plastic debris in the long term. These should be focused on provide information on the fauna associated to these habitats (and how this can locally change in relation to the different plastic concentration and composition within wrecks), such as on the chemical composition of plastic debris. These information are essential to increase the knowledge base regarding the plastic pollution affecting the area and the related effects on marine coastal environments.

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Ethical statement

The authors confirmed that they have respected all the local, national, and international regulations and conventions, and normal scientific ethical practices. The manuscript does not contain any studies with human participants or animals.

CRediT authorship contribution statement

Serena Savoca: Writing – review & editing, Visualization, Supervision, Resources, Conceptualization. **Nunziacarla Spanò:** Validation, Supervision, Resources. **Irina Litvinenko:** Methodology, Data curation, Conceptualization. **Joseph A. Borg:** Supervision, Resources, Methodology, Conceptualization. **D'Iglio Claudio:** Writing – review & editing, Visualization, Data curation. **Tosin Afeniforo:** Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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