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The power of *Posidonia oceanica* meadows to retain microplastics and the consequences on associated macrofaunal benthic communities☆

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ABSTRACT

In the coastal environment, a large amount of microplastics (MPs) can accumulate in the sediments of seagrass beds. However, the potential impact these pollutants have on seagrasses and associated organisms is currently unknown. In this study, we investigated the differences in MPs abundance and composition (i.e., shape, colour and polymer type) in marine sediments collected at different depths (−5 m, −15 m, −20 m) at two sites characterized by the presence of *Posidonia oceanica* meadows and at one unvegetated site. In the vegetated sites, sediment samples were collected respectively above and below the upper and lower limits of the meadow (−5 m and −20 m), out of the *P. oceanica* meadow, and in the central portion of the meadow (−15 m). By focusing on the central part of the meadow, we investigated if the structural features (i.e. shoots density and leaf surface) can affect the amount of MPs retained within the underlying sediment and if these, in turn, can affect the associated benthic communities. Results showed that the number of MPs retained by *P. oceanica* meadows was higher than that found at the unvegetated site, showing also a different composition. In particular, at vegetated sites, we observed that MPs particles were more abundant within the meadow (at – 15 m), compared to the other depths, on unvegetated sediment, with a dominance of transparent fragments of polypropylene (PP). We observed that MPs entrapment by *P. oceanica* was accentuated by the higher shoots density, while the seagrass leaf surface did not appear to have any effect. Both the abundance and richness of macrofauna associated with *P. oceanica* rhizomes appear to be negatively influenced by the MPs abundance in the sediment. Overall, this study increases knowledge of the potential risks of MPs accumulation in important coastal habitats such as the *Posidonia oceanica* meadows.

1. Introduction

In the last decades, the use of plastic material has exponentially increased, and most of the plastic produced ends up as marine waste (Guzzetti et al., 2018). To date, approximately 80% of global marine litter is of plastic origin (IUCN, 2021), and it is estimated to reach more than 100 million tonnes in 2025 (Gurjar et al., 2023), raising the need for governments to incentivize special surveillance of marine ecosystems worldwide (Simon et al., 2021).

The origin of this waste can be attributed to numerous sources, such as industrial and domestic discharges, fishing, coastal activities and tourism. It has been demonstrated that the wastes may have a strong impact on marine habitats, due to its capacity to persist and accumulate in the ecosystem (Derraik, 2002; Ostle et al., 2019; Nawab et al., 2023). Once in the ocean, the plastic is fragmented by physical, chemical and biological processes into particles smaller than 5 mm, i.e. microplastics (MPs) (Law and Thompson, 2014), which are ubiquitous in all marine environments (Pereira et al., 2023; Wilcox et al., 2019). MPs are a

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heterogeneous group of particles differing in size, density, shape, colour and chemical composition, depending on their origin and the ecological processes (e.g. degradation process) they encounter in the marine environment (Liu et al., 2022; Nawab et al., 2023). MPs adversely affect marine ecosystems, due to their potential transfer through the marine food webs by the ingestion and accumulation in different trophic levels (Costa et al., 2020; Darabi et al., 2021; Díaz-Jaramillo et al., 2021).

In fact, there are numerous testimonies reporting negative effects of MPs on marine species, both in the early larval and adult stages of invertebrates and vertebrates (Martínez-Gómez et al., 2017), highlighting physical damage (Jovanović, 2017), causing toxicity reactions (Tibiriçá et al., 2019; Palmer and Herat, 2021) and generating behavioural disturbances (Varó et al., 2021). Additionally, biofragmentation (So et al., 2022) and sedimentation of MPs (Coppock et al., 2021) can have detrimental consequences, not only on individual organisms but also on marine communities (Green, 2016).

MPs are most abundant in near-shore environments (Buckingham et al., 2022) and in shallow habitats such as seagrass meadows (Menicagli et al., 2022; Walther and Bergmann, 2022), which are complex marine ecosystems rich in biodiversity and highly vulnerable to anthropogenic impacts (Unsworth et al., 2021). Besides serving as a nursery, foraging and refuge areas for many organisms, seagrass meadows provide important ecosystem services for human wellbeing (Boudouresque et al., 2016; Ruiz-Frau et al., 2017). For example, they act as a natural sink for carbon uptake (Mazarrasa et al., 2018) and, by their three-dimensional structures (i.e. leaves, rhizomes and the so-called matte, formed by an intertwining of roots, rhizomes and sand), trap both the organic and inorganic suspended particles, including MPs, thus preventing their dispersion along coastal areas (Huang et al., 2020; Kennedy et al., 2010; Huang et al., 2021; Gerstenbacher et al., 2022; Lee et al., 2022; Wright et al., 2023).

In the Mediterranean Sea, one of the most important seagrasses is *Posidonia oceanica*, an endemic species forming extensive meadows from the surface down to 40 m (Bay, 1984). The articulated three-dimensional framework it forms contributes to the reduction of wave motion, favours sediment accumulation (Dahl et al., 2021) and facilitates the sinking of MPs underneath the meadow (Navarrete-Fernández et al., 2022), especially when the meadows are characterized by high shoots density (Unsworth et al., 2021).Nevertheless, the accumulation of MPs could negatively affect *P. oceanica* meadows, causing plastic incorporation into the seagrass food web through direct or indirect MPs ingestion by the associated marine species (Wright et al., 2013), with detrimental consequences on the whole associated community.

This study aims to investigate the potential ability of *P. oceanica* meadows to trap MPs, by comparing vegetated and unvegetated coastal sites. As a consequence, we explored, at vegetated sites, whether the structural features of *P. oceanica* meadows (i.e. shoots density and leaf surface area) can affect the amount of MPs retained within the underlying sediment and whether these, in turn, can affect the associated benthic communities. To achieve these objectives, we assessed i) whether the abundance and composition (i.e. shape, colour and polymer type) of MPs differed between the marine sediments collected from two sites characterized by the presence of *P. oceanica* and at an unvegetated site at increasing depth from the coast, ii) whether, at vegetated sites, differences in *P. oceanica* shoot density and leaf surface area can influence MPs abundance in the sediment underneath the meadows and iii) whether MPs abundance can influence the macrofaunal benthic community associated with the meadows.

2. Materials and methods

2.1. Study area and MPs sampling

The study was performed within three coastal sites located along southern Sicily, to specifically we selected: 1) two sites for the presence of extensive *Posidonia oceanica* meadows (growing both on matte and on sandy bottoms), "Sciacca" (SC VEG; geographical coordinates: N 37°30′18″, E 13°04′ 28″) and "Portopalo di Capo Passero" (PP VEG; geographical coordinates: N 36°40′ 55″, E 15°08′ 15″), and 2) one unvegetated site (a sandy bottom), "Gela" (GE NO-VEG; geographical coordinates: N 37°03′ 47″, E 14°14′ 48″) used as control (Fig. 1). The three sites are located near urbanized areas and are strongly influenced by anthropogenic activities such as intensive agriculture in particular greenhouse cultivation with plastic sheeting.

For the study of MPs, within each site, sediment samples were collected at three depths, −5 m, −15 m and −20 m, including different stations located along transects perpendicular to the coastline (Table S1). In the vegetated site, the bathymetries were selected to coincide with unvegetated sediments above and below of the upper and lower limits of the meadow (−5 and −20 m), and with the central area of the meadow (−15m).

We randomly selected three transects in Gela and six transects in Sciacca and Portopalo (since the lower limit of the meadow in Portopalo di Capo Passero exceeded - 40 m and it was not accessible to the underwater operators, samples were collected only at −5 and −15 m).

At each station, three samples of sediment spaced 5 m apart were collected by scuba divers. The fieldwork was carried out during September and October 2019, collecting 54 samples at Sciacca, 36 samples at Portopalo di Capo Passero (since the lower limit of the meadow exceeded - 40 m and it was not accessible to the underwater operators) and 27 samples at Gela. Replicates consisted of 200 g of surface sediment manually collected between the rhizomes, using steel cores, and immediately stored at −20 °C until processing.

2.2. MPs analysis

2.2.1. Extraction

Sediment samples were dried at 50 °C for 48 h prior to sieving; specifically, 200 g of sediment were sorted through a stainless-steel sieve with a 5 mm mesh diameter for 15 min. The retained sediment was weighed and stored in glass Petri dishes until the extraction by a density separation method (Hanke et al., 2013). Sieved sediments were transferred into a glass beaker and topped up to a volume of 1 l with saturated NaCl solution (1.2 g cm^{-3}) (Prata et al., 2019). The mixture was stirred on a Teflon-coated magnetic stirrer at 1000 rpm and let to decant for 10 min. The lighter particles, among which plastics, were separated from the heavier ones. The supernatant was then collected, by using a 100 ml glass syringe with a 5 mm aperture diameter and transferred to a glass beaker covered with aluminium foil. The separation procedure was repeated three times with each sample to ensure a total recovery (100%).The separated solution was filtered by a glass filtration set equipped with a vacuum pump and through 47 mm Whatman GF/C filters (1.2 μm porosity). Filters were stored in sealed glass Petri dishes prior to examination and sorting of the putative plastic particles under the stereomicroscope. Since a very low quantity of organic material remained on the filters after the density separation process, before sorting, 4–5 drops of H_2O_2 solution (10%) were added directly on the filters to digest it (Prata et al., 2019). All values were expressed in terms of n. items/Kg dry weight (mean ± SD).

2.2.2. MPs identification

Filters were examined inside the sealed Petri dishes under the stereomicroscope (Leica M80) and photographed by a digital camera (Leica IC90E). All pictures of the identified particles were analysed with the software ImageJ to measure the MPs' lengths and associate them to different categories of shape (fibre, fragment, rope, film, line and foam) and colours, according to the technical subgroup of the Marine Strategy Framework Directive for marine litter (Hanke et al., 2013). To define the MPs polymeric composition, all items within each sample were chemically identified with a FT-IR spectrophotometer (PerkinElmer Spectrum Two) recording infrared spectra in ATR mode. For smaller particles, the

Fig. 1. Study area. "Sciacca" and "Portopalo di Capo Passero" were selected for the presence of extensive *Posidonia oceanica* meadows (vegetated sites) and "Gela" was the unvegetated control site.

chemical analysis was implemented with a μFT-IR (Thermo Scientific™ Nicolet™ iN10). The obtained spectra were then compared with a library of standard polymeric spectra and accepted with a similarity threshold of more than 70%, in line with suggestions from previous studies (Wakkaf et al., 2020). A control procedure was used following Pittura et al. (2022) in order to reduce the contamination that may occurs in the working space and to avoid the overestimation of MPs in the samples.

2.3. Sampling of Posidonia oceanica meadow and associated macrofaunal communities

To contextually characterize the main seagrass meadow features and the associated benthic macrofauna, a further sampling was performed at −15 m depth in the vegetated sites within the *P. oceanica* meadows (S1 – 6 at SC VEG site and P1 – 6 at PP VEG site).

The characterisation of *P. oceanica* meadows was carried out according to Scardi et al. (2006). In both vegetated sites, *P. oceanica* shoot density was estimated using a quadrat of 40 × 40 cm. In detail, for each station at −15 m, three replicates were randomly placed in three areas (20 × 20 m) 10 m apart. The mean number of shoots recorded at each station was converted into density (n. shoots/m^2). Further, orthotropic shoots were collected at each station (6 shoots × 3 areas), placed in cotton bags and stored at −20 °C until lab analysis. For each shoot, leaf length and width were measured to estimate the leaf surface area (cm^2/shoots).

The fauna associated with *P. oceanica* rhizome layer was sampled by SCUBA divers. For each station located at −15 m, three samples of macrofauna were collected within a 40 × 40 cm quadrat, by an air lift sampler (Templado et al., 2010), consisting of a PVC pipe (80 cm long and with an inner diameter of 8 cm) connected at its lower end with a SCUBA cylinder. The other end was attached with an interchangeable 0.5 mm mesh bag within which the captured organisms were collected and preserved in a 70% ethanol solution. Once in the laboratory, macrofaunal specimens were sorted under a stereomicroscope (Leica M8) and identified to the lowest possible taxonomic level. All the results were expressed as mean ± SD.

3. Statistical analysis

Univariate and multivariate distance-based permutational non-parametric analyses of variance (PERMANOVA; Anderson, 2001; McArdle and Anderson, 2001) were performed to test differences in MPs abundance and composition (i.e. shape, colour and polymer type) between vegetated and unvegetated sites (fixed factor "Site" with 3 levels: SC VEG, PP VEG and GE NO VEG), among transects (random factor "Transect", nested in "Site", with levels at SC VEG and PP VEG, and 3 levels at GE NO-VEG) and among depths along the transects (fixed factor "Depth" with 3 levels at SC VEG and GE NO-VEG: −5 m, −15 m and −20 m, and 2 levels at PP VEG: −5 m and −15 m). PERMANOVAs were based on Euclidean distance ordinated matrices using 9999 permutations of residuals under a reduced model with a Type III (partial) sum of squares. When significant differences were observed, a-posteriori pairwise test among pairs of levels within the factor was performed.

In the vegetated sites, differences in the structural features of *P. oceanica* meadows (*i.e* shoots density and leaf surface area) and in macrofaunal abundance, taxa richness (of the total community and of the dominant groups: Crustacea, Polychaeta and Mollusca) and community composition between the sites and among sampling stations, located within the meadows (at −15 m), were also tested by PERMANOVA (one fixed factor "Site" with 2 levels and one random factor "Station", nested in "Site", with 6 levels). For *P. oceanica* parameters the analyses were performed on Euclidean distance ordinated matrices, while for the macrofauna, square-root transformed data were ordinated by the Bray-Curtis dissimilarity (adding a dummy value when the resemblance between two samples was undefined). The analyses were carried out with 9999 permutations of residuals under a reduced model with a Type III 208 (partial) sum of squares (Anderson, 2001).

To investigate whether shoot density and the leaf surface area of *P. oceanica* influenced the MPs abundance, linear regression analyses were tested for significance (OriginPro, 2016). Since we detected significant differences in *P. oceanica* features between the two sites, we performed the regression analysis separately for each site. Finally, to identify the potential drivers (i.e. *P. oceanica* features or MPs abundance) of macrofauna abundance, taxa richness and community composition, in addition to linear regressions, a distance-based redundancy analysis (dbRDA) based on the Bray– Curtis dissimilarities and a nonparametric multivariate multiple regression analysis using the routine "DISTLM forward" (McArdle & Anderson, 2001) were executed. Statistical analyses were performed using the PRIMER v6 software (Clarke, 2005).

4. Results

4.1. MPs abundance and composition

MPs abundance showed significant differences among all the investigated factors (i.e., Site, Transect and Depth; Table 1). *A-posteriori* pairwise comparison showed that the abundance of MPs at −15 m was significantly higher at the two vegetated sites compared to the control ($p < 0.05$; Table 1; Fig. 2) and, only at the vegetated sites, the MPs abundances at −15 m were significantly higher compared to the other surveyed depths (pairwise, $p < 0.01$; Table 1; Fig. 2).

The composition of MPs in terms of shape, colour and polymer type significantly differed between vegetated and unvegetated sites (Table S2) only at −15 m of depth (pairwise, $p < 0.05$; Tables S2 and S3). Furthermore, MPs characteristics at vegetated sites significantly varied between −15 m and the other depths along the transect (PERMANOVA, $p < 0.05$; Table S3). At −15 m, in all the investigated sites, fragment resulted the dominant shape, representing 92% and 82% of the total MPs respectively found at the sites SC VEG and at PP VEG, and 52% at the control GE NO-VEG (Fig. S1). Transparent was the dominant MPs colour at all the sites, representing the 88%, the 80% and the 38% of the items at SC VEG, PP VEG and GE NO-VEG, respectively (Fig. S1). Concerning the MPs polymer type, the 100% of the MPs at the control site was represented by polypropylene (PP), while it represented the 76% and 81% of the items found at the sites PP VEG and SC VEG, followed by polyethylene (PE; 10% at PP VEG and 13% at SC VEG). At PP VEG, the 8% of MPs was made of polyamide (PA), while all the other typologies of polymers did not exceed the 6% at both vegetated sites (Fig. S1).

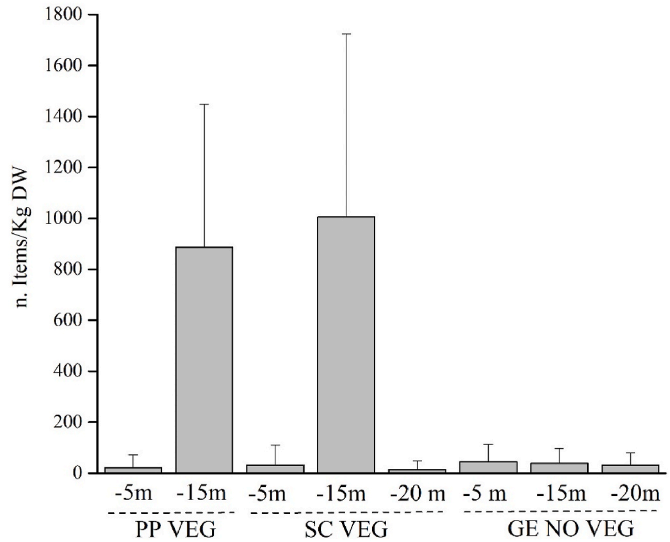

Fig. 2. Microplastic abundances (Mean ± SD) in the sediments at vegetated (SC VEG and PP VEG) and unvegetated sites (GE NO VEG) across the different sampling depths. This graph shows the average of the values measured in all stations sampled at each depth along the transect in each site (6 for PP VEG and SC VEG and 3 for GE NO VEG).

Table 1
Results of the PERMANOVA analysis comparing the abundance of microplastics (MPs) between vegetated and unvegetated sites, among transects and among different depths. df = degrees of freedom, MS = mean square, Pseudo-F=F statistic, P(perm) = probability level. Statistically significative values are in bold.

Main Test Source	df	MS	Pseudo-F	P (perm)
Site	2	1.03E+06	4.16	**0.0385**
Depth	2	4.30E+06	17.53	**0.0002**
Transect(Site)	12	2.55E+05	2.99	0.0019
Site×Depth	3	1.37E+06	5.60	**0.0075**
Transect(Site)×Depth	19	2.45E+05	2.88	**0.0007**
Residuals	78	8.50E+04		
Total	116			

Pair wise: Term 'SitexDepth' for pairs of levels of factor 'Site'

	- 5m		−15m		−20m	
Group	**T**	**P (perm)**	**T**	**P (perm)**	**T**	**P (perm)**
PP VEG, GE NO-VEG	1.63	0.1574	2.74	**0.0234**		
PP VEG, SC VEG	0.61	0.5311	0.41	0.6524		
GE NO-VEG, SC VEG	0.55	0.5361	3.27	**0.0240**	1.80	0.14

Pair wise: Term 'SitexDepth' for pairs of levels of factor 'Deep'

	PP VEG		SC VEG		GE NO-VEG	
Group	**T**	**P (perm)**	**T**	**P (perm)**	**T**	**P (perm)**
-5m, −15m	4.15	**0.0097**	4.49	**0.0094**	3.46	0.1495
-5m, −20m			2.21	0.0833	11.50	0.1066
−15m, −20m			4.77	**0.0060**	2.75	0.1627

4.2. Effect of P. oceanica features on MPs distribution

The MPs abundances in the sediments within the surveyed *P. oceanica* meadows showed significant differences among the sampling stations at −15 m of depth (PERMANOVA, $p < 0.05$; Table S4), ranging from 458 ± 250 items/Kg DW at SC VEG to 1890 ± 220 items/Kg DW at PP VEG. Also, MPs shape and colour significantly differed among the surveyed stations (PERMANOVA, $p < 0.05$, Table S4). *P. oceanica* shoot density showed significant differences both between the two vegetated sites and among stations at −15 m ($p < 0.01$, Table S4), ranging from 289.6 ± 19.1 shoots/m^2 at SC VEG to 601.4 ± 71.8 shoots/m^2 at PP VEG. Instead, the values of leaf surface area significantly differed only between sites ($p < 0.01$; Table S4), ranging from 175.7 ± 40.4 cm^2/shoots at PP VEG to 284.4 ± 6.7 cm^2/shoots at SC VEG. In addition, the regression analysis showed a significant positive correlation between the shoot density and the MPs abundance at both sites ($r^2 = 0.74$, $p < 0.05$ for PP VEG and $r^2 = 0.81$, $p < 0.05$ for SC VEG; Fig. 3). No significant correlation was observed between leaf surface area and MPs.

4.3. Effect of MPs on macrofauna associated to P. oceanica meadows

Macrofauna associated with the *P. oceanica* rhizome layer showed significant differences among the sampling stations in terms of total abundance, taxa richness and community composition (PERMANOVA, $p < 0.001$; Table S5). Abundances ranged from 5.3 ind. ± 3.2 to 103.3 ind. ± 3.8, while the taxonomic richness varied from 4 taxa ±5 to 48 taxa ±5 at SC VEG and PP VEG, respectively. Both the macrofaunal abundance and the taxa richness were negatively correlated with the MPs abundance ($r^2 = 0.27$, $p < 0.05$ and $r^2 = 0.30$, $p < 0.05$, respectively, Fig. S2 A and B), while they showed no correlation with the *P. oceanica* shoot density and leaf surface area. Also, the multivariate multiple regression analysis (DistLM; Table S6) and the dbRDA analysis (Fig. 4) showed that the differences in macrofaunal abundance and taxa richness among stations were mainly explained by the MPs abundance in the meadows (~30% of the variance). Analysing the three main macrofaunal groups separately (Crustacea, Polychaeta and Mollusca), significant differences among the stations were observed, both in

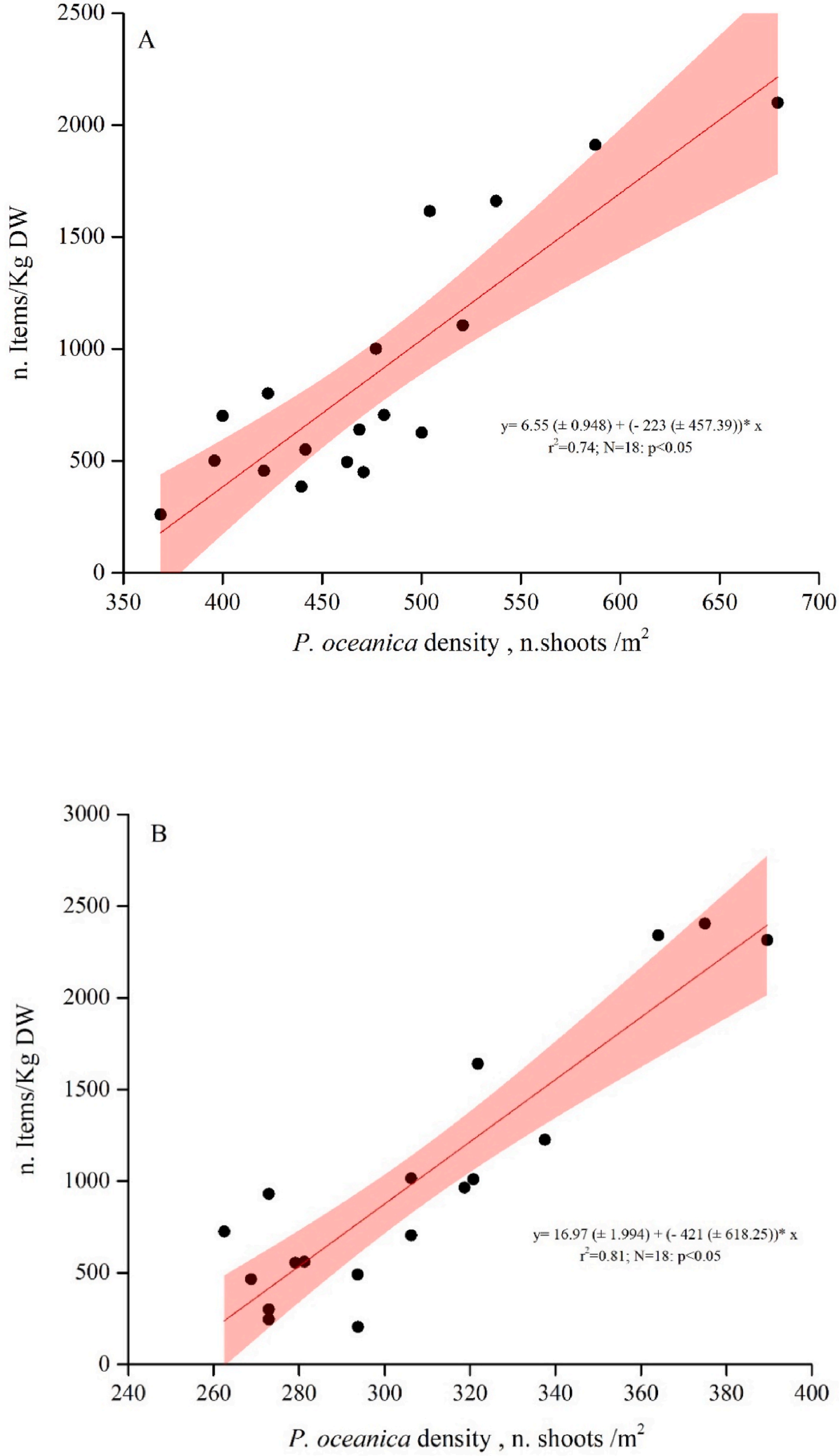

Fig. 3. Correlation between microplastic abundance (n. Items/Kg DW) and *Posidonia oceanica* density (shoots/m^2) at the stations located at −15 m at the two vegetated sites: A) PP VEG and B) SC VEG. The thick lines represent the regression while the faded bands represent the 95% confidence interval.

abundance and taxa richness ($p < 0.01$; Table S5). For Crustacea and Mollusca these differences were mainly explained by the MPs abundance (DistLM; from 11% to 17% of the variance, except for Mollusca richness), while for the group Polychaeta, the features of the meadow were responsible for a greater fraction of variance (from 15% to 34%; Table S6). Indeed, the regression analysis showed significant negative correlations between MPs concentrations and the abundance and diversity of Crustacea ($r^2 = 0.30$, $p < 0.05$; Fig. S2 C and D) and Mollusca ($r^2 = 0.14$, $p < 0.05$; Fig. S2 E and F), while Polychaeta were positively related with the meadow density ($r^2 = 0.30$, $p < 0.05$; Fig. S2 G and H).

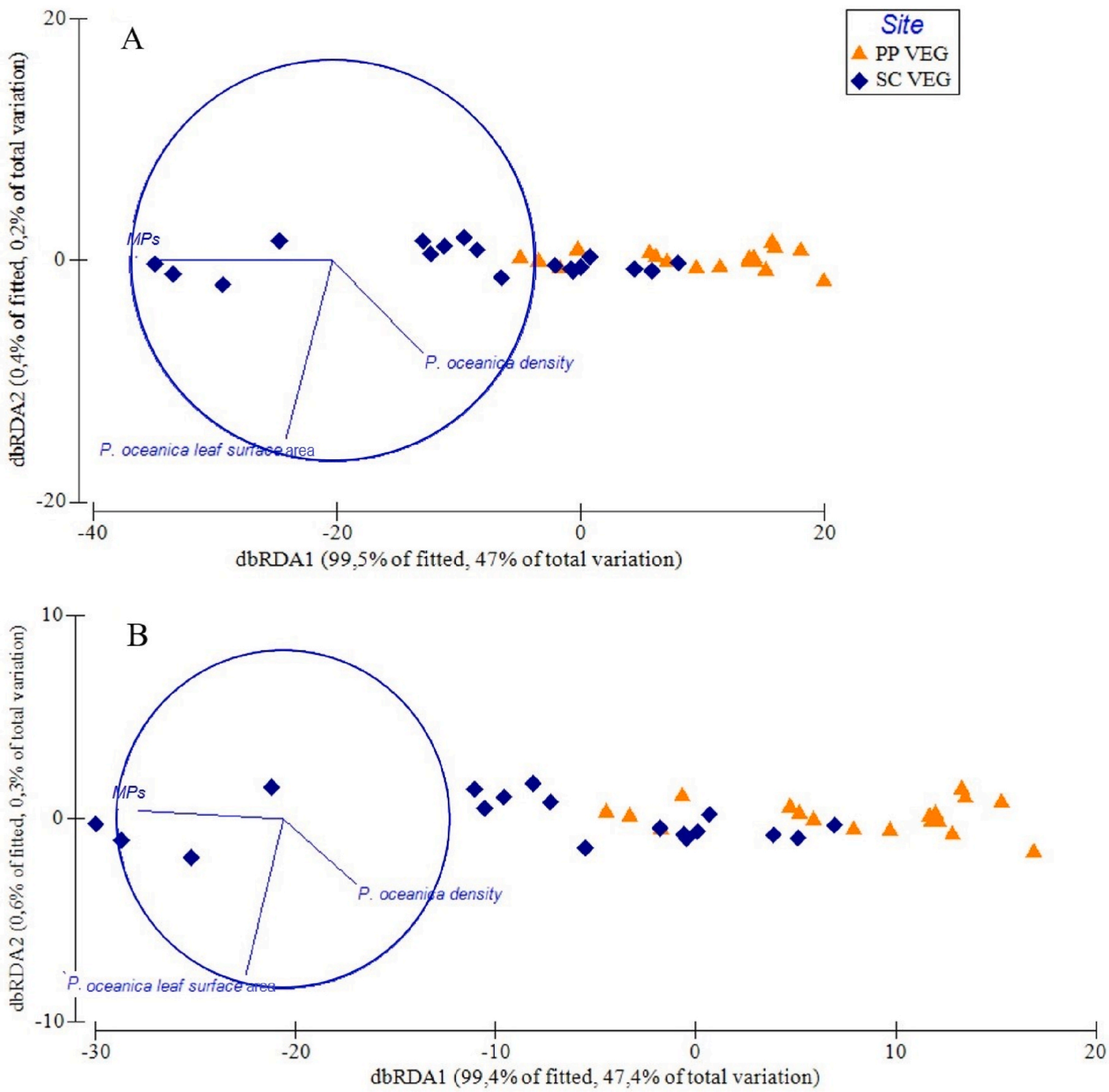

Fig. 4. Distance-based redundancy analysis (dbRDA), showing the relationships between *P. oceanica* features (i.e., shoots density and leaf surface area) and microplastics (MPs) and A) macrofaunal abundance and B) taxa richness in the two vegetated sites.

A List of the macrofaunal taxonomic groups found within the stations at – 15 m of depth at the two vegetated sites is reported in Table S7.

5. Discussion

5.1. Effect of *P. oceanica* on the MPs distribution and composition

In this study, we found a greater accumulation of MPs in sites characterized by the presence of a *P. oceanica* meadow compared to the unvegetated control site, with the highest MPs amount found within the seagrass meadow at – 15 m of depth. Comparing the vegetated and unvegetated habitats, indeed, the distribution of MPs only differed at the depth of −15 m. If the MPs input did not differ among the three surveyed sites, this result could suggest that at the unvegetated site, floating MPs are homogeneously dispersed at the studied depths, while at the vegetated sites the seagrass meadow acts as a filter by trapping the plastic particles within its complex three-dimensional structure. Indeed, while macroplastics tend to accumulate along the edge of the meadow, MPs can penetrate a few meters into it, reaching the inner part of the meadow (Navarrete-Fernàndez et al., 2022). Higher MPs abundance has been also reported in meadows of other seagrass species, such as *Zostera marina*, *Enhalus acodoide*, *Halophila beccarii* and in a mangrove forest dominated by A*vicennia marina* compared to their corresponding unvegetated sites (Huang et al., 2020, 2021; Jones et al., 2020). Overall, our results showed that fragments were the most common shape of MPs, found in both vegetated and unvegetated sites, consistent with previous studies in the Mediterranean Sea (Sanchez-Vidal et al., 2021; Pittura et al., 2022). However, in our study, the vegetated sites had a much higher percentage of fragments than the unvegetated control, possibly because their irregular shape makes them easier to be trapped by *P. oceanica* leaves (Sanchez-Vidal et al., 2021). According to recent research, several seagrass species (*Cymodocea rotundata, C. serrulata* and *Thalassia hemprichii*) can trap high amounts of MPs through their adhesions to the leaf surface (Seng et al., 2020). This can be attributed to both the presence of epiphytes on seagrass leaves and the development of a biofilm on the plastic particles that increases their stickiness on marine seagrasses (Goss et al., 2018; Jones et al., 2020). Moreover, epiphytic bacteria commonly found on the seagrass leaves may embed MPs particles, accelerating the formation of high-density plastic aggregates, which facilitate their sinking and accumulation in the sediment (Michels et al., 2018; Zhao et al., 2022). It is also important to note that the amount of transparent items increased in both vegetated sites compared to the control one. This result suggests the potential change of MPs toward light colours (discoloration or bleaching), due to the higher probability that biodegradation, chemical degradation and photo-degradation phenomena occur at the rhizomes stratum in *P. oceanica* meadows, where greater bacterial activities take place (Liu et al., 2022; Bonanomi et al., 2023). Considering the chemical composition, we found that PP was the only type of polymer present in the control site, whereas the vegetated sites were also characterised by the presence of other polymers such as PE, PA, polyethylene terephthalate (PET) and polyvinyl chloride (PVC). This is probably related to the fact that, the meadow represents a long-term accumulation site, so even less common polymers were found in it, simply because they have had more time to settle. Additionally, as polymers long-term deposits other Mediterranean sedimentary systems have shown similar polymer type (Mistri et al., 2020; Piazzolla et al., 2020; Sayed et al., 2021; Boskovic et al., 2022). Furthermore, it has been shown that the variability in term of polymer composition is strictly related to the marine area sampled (Erni-Cassola et al., 2019), as the accumulation pattern of polymers in the marine environment is related to their multifaceted features combined with marine dynamics and vertical mixing (Brunner et al., 2015; Kooi et al., 2016) that define their accumulation pattern. Moreover, coastal sediments have been described as the main sink of all common polymers found in the aquatic environment (Woodall et al., 2014). Finally, the predominant presence of PP in all the samples can be related to the presence of intense agricultural activity along the southern coasts of Sicily. The use of plastic sheeting made entirely of PP or PE is common during summer to protect cultivated fields from strong summer radiation and other environmental factors is widespread. Alongside seagrass presence, we found that the MPs entrapment by *P. oceanica* was accentuated by the higher meadow density (i.e., the seagrass shoots density), while the seagrass leaf surface area does not appear to have any effect. Accordingly, high shoot density in seagrass meadows is reported to significantly reduce turbulent wave energy and to accumulate more MPs in the underneath sediment compared to low shoot density meadows (de Los Santos et al., 2021; de Smit et al., 2021; Unsworth et al., 2021).

5.2. Impact of MPs on the macrofauna associated to P. oceanica meadows

Current research on MPs has mainly focused on the direct interaction of benthic organisms with plastics and their accumulation in animal tissues (So et al., 2022), but few studies describe the MPs effects on benthic assemblages and communities in highly diverse ecosystems, such as seagrass meadows (Green, 2016; Gerstenbacher et al., 2022). For example, it was observed that high abundance of MPs in oyster reefs may alter the associated benthic assemblages by reducing the abundance of organisms (Green, 2016).

Posidonia oceanica meadow is a biodiversity hotspot and nursery area for many benthic species living on or close marine sediments (Boudouresque et al., 2016). An accumulation of MPs in the sediments underneath the *P. oceanica* meadow may increase the exposure risk for benthic organisms to meet plastic fragments within the sediments (Coppock et al., 2021), entailing potential negative consequences for the biota. In our research the macrofauna abundance and taxa richness associated to *P. oceanica* meadows appeared to be negatively influenced by the high abundance of MPs in the sediment, corroborating Tahir et al. (2019), which showed that an elevated plastic abundance within different seagrass meadows corresponds to high levels of contamination in sediment-associated organisms. Indeed, the MPs capacity to adsorb and transport heavy metals and other pollutants into marine sediments increases the risk of transferring these contaminants to the organisms (Cauwenberghe et al., 2015; Li et al., 2020; Nawab et al., 2023). This can cause high levels of toxin accumulation in animal tissues, generating negative reactions in macrofaunal communities associated with the seagrasses (Gerstenbacher et al., 2022). Although in seagrass habitats, the abundance and species composition of the associated fauna are generally related to the plant characteristics (e.g., the shoot density which provides more protection from predation, Orth et al., 1984), our results showed no correlation between *P. oceanica* features and the associated macrofaunal community, suggesting a greater influence of MPs presence on the abundance and the diversity of organisms.

Specifically, the abundance and diversity of Crustacea and Mollusca resulted negatively influenced by the abundance of MPs, according to other studies (Digka et al., 2018; Cau et al., 2020; Expósito et al., 2022; Yin et al., 2022). A possible explanation could be a higher chance for filter feeders to ingest MPs (Sussarellu et al., 2016), as it was observed that these organisms can have the capacity to reduce the effects of MPs through particular defence mechanisms; however there is a limit of accumulation beyond which these fail, and thus physiological functions are compromised (Wang et al., 2021; Khanjani et al., 2023). Crustacea and Mollusca could also implement selective ingestion behaviour on MPs by retaining only those particles that, due to their size, are mistaken for prey (Sussarellu et al., 2016; Woods et al., 2018; Li et al., 2021; Sorrentino and Senna, 2021; Wang and Wang, 2023). Several experimental studies showed that the effects of MPs can be reduced by rejecting undesirable particles through faces and pseudofeces. However, in the marine environment where the MPs are persistently present and vary in form and roughness, the probability to egest them is reduced and thus the probability of accumulation may be higher (Sussarellu et al., 2016; Woods et al., 2018). Although in our study we found a large accumulation of MPs in vegetated sites, we do not know how long the faunal assemblage within the meadows has been exposed to the MPs. Moreover, the fragment shape, which is dominant within the surveyed seagrass meadows, is known to have a more harmful effect on these macrofaunal groups (Gonçalves et al., 2019; Zhang et al., 2023). By contrast, in our study, Polychaeta appeared more influenced by the density of *P. oceanica* than MPs abundance probably because of the ability of these organisms, in particular of deposit feeder species, to excrete MPs with no significant effects on their health (Kaposi et al., 2014; James et al., 2023; Porter et al., 2023). However, this suggests that these organisms, may promote the biofragmentation through processes of ingestion and egestion of MPs, making them more available in the ecosystem for smaller organisms (So et al., 2022).

5.3. Conclusion

Our study reinforces the concept that vegetated substrates may represent natural plastic sinks (Sanchez-Vidal et al., 2021) and contributes to advance current knowledge on the potential risks posed by MPs to important coastal key habitats such as the *P.oceanica* meadows, elucidating detrimental consequences on the biodiversity they host. Results highlight the need for further research to better understand the multiple-scale effects of MPs on marine ecosystems. Improving the knowledge of mechanisms such as microplastic retention in seagrass meadows, indeed, is a key point to enhance the management of Mediterranean habitats with high ecological value and to implement effective strategies for their conservation, including developing precautionary measures to mitigate the effect of MPs pollution on the environment and, consequently, on human health.

CRediT authorship contribution statement

Marco Martinez: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Roberta Minetti:** Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation. **Emanuela Claudia La Marca:** Writing – review & editing. **Valeria Montalto:** Writing – review & editing. **Alessandro Rinaldi:** Writing – review & editing. **Elisa Costa:** Writing – review & editing, Methodology. **Fabio Badalamenti:** Writing – review & editing. **Francesca Garaventa:** Writing – review & editing, Methodology, Conceptualization. **Simone Mirto:** Writing – review & editing, Funding

acquisition. **Francesca Ape:** Writing – review & editing, Writing – original draft, 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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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