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Dune plants as a sink for beach litter: The species-specific role and edge effect on litter entrapment by plants

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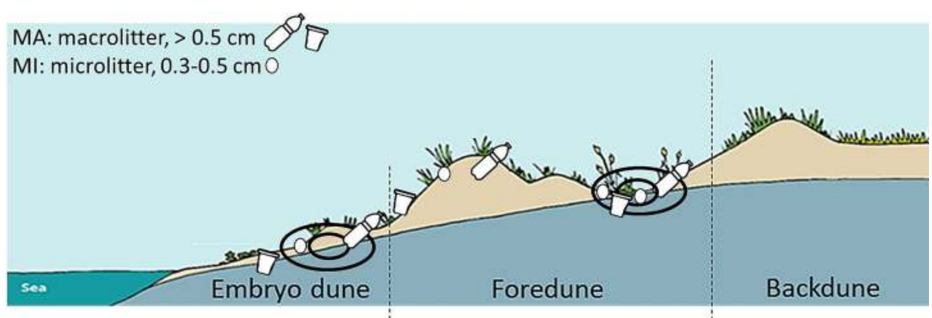
HIGHLIGHTS

- Dune vegetation entrapped macro- and microlitter.
- Trap efficiency was higher for prostrate plants than not prostrate plants.
- 'Plant-edge litter effect': plant edge captured more litter than the core area.
- Plant morphology also had a significant effect on the litter trapping.
- The more articulated plant structure, the wider the litter size range it can trap.

GRAPHICAL ABSTRACT



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ABSTRACT

Anthropogenic litter accumulates along coasts worldwide. In addition to the flowing litter load, wind, sea currents, geomorphology and vegetation determine the distribution of litter trapped on the sandy coasts. Although some studies highlighted the role of dune plants in trapping marine litter, little is known about their efficiency as sinks and about the small-scale spatial distribution of litter across the dune area. Here, we explore these gaps by analysing six plant species widespread in Mediterranean coastal habitats, namely *Echinophora spinosa*, *Limbarda crithmoides*, *Anthemis maritima*, *Pancratium maritimum*, *Thinopyrum junceum,* and *Salsola kali*. The present study analyses for the first time the capture of litter by dune vegetation at a multi-species level, considering their morphological structure. Data on plastic accumulation on dune plants were compared with unvegetated control plots located at embryo-dune and foredune belts. We found that dunal plants mainly entrapped macrolitter (> 0.5 cm). Particularly, *E. spinosa*, *L. crithmoides*, *A. maritima* and *P. maritimum* mostly accumulated litter in the embryo dune while *T. junceum* and *S. kali* entrapped more in the foredune area. Moreover, beach litter was mainly blocked at the edge of the plant patches rather than in the core, highlighting the 'Plant-edge litter effect'. As *A. maritima* and *S. kali* entrapped respectively more litter in embryo and foredune habitats, these species could be used to monitor and recollect litter. In this light, our findings provide further insight into the role of dune plants in the beach litter dynamics, suppling useful information for beach clean-up actions.

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1. Introduction

Marine litter represents a wide global concern affecting ecosystems, posing a risk to human welfare (UNEA, 2019; Veiga et al., 2022). The persistent plastic materials are the predominant component of marine litter (80 % in abundance, Morales-Caselles et al., 2021), and the production of packaging and other plastic products increases year by year (Plastics Europe, 2021).

Anthropogenic pollution in the Mediterranean Sea is largely provided by three main driving forces, related to the high human pressure together with the confinement of this semi-enclosed basin (Cózar et al., 2015). The first is related to high coastal population and tourism (UNEP, 2012, Suaria and Aliani, 2014, Prevenios et al., 2018). The second one is related to the strong maritime activity, including shipping, fishing, industrial, and other coastal activities (Cózar et al., 2015; Sharma et al., 2021). The third factor, instead, regards the riverine transport of macrolitter from land to the sea, rising litter pollution in marine and coastal zones (Crosti et al., 2018; Gallitelli et al., 2020; González-Fernández et al., 2021; Gallitelli and Scalici, 2022; Poeta et al., 2022; Veiga et al., 2022; Cesarini et al., 2023; González-Fernández et al., 2023).

The distribution of beach litter on the coasts depends on both abiotic and biotic factors (Morales-Caselles et al., 2021; Gallitelli et al., 2021). The interplay of wind, water currents and tides largely drives the movement of litter across shores (Galgani et al., 2015). Particularly, complex interactions among aeolian processes, sediment transport, nearshore hydrodynamics, and dune vegetation shape dunes morphology (Sherman and Bauer, 1993; Malvárez et al., 2019; Andriolo et al., 2020; Corbau et al., 2023). Together with vegetation density, those factors influence litter dynamics on beaches (Andriolo et al., 2020; Gallitelli et al., 2021; Mo et al., 2021). Indeed, animals and plants can interfere with litter distribution. Specifically, dune and coastal vegetation (including natural litter such as wrack) trap plastic pieces, entangling them within their structure (Battisti et al., 2020a, 2020b; Gallitelli et al., 2021; Andriolo et al., 2021; Gallitelli et al., 2023). According to several previous studies, marine litter is highly abundant in coastal habitats worldwide (Ivar do Sul and Costa, 2007; Galgani et al., 2013; Munari et al., 2016; Šilc et al., 2018b; Gonçalves et al., 2020). Particularly, litter showed an accumulation pattern decreasing from the shoreline and embryo dunes to the inner-dune habitats with mobile and fixed dunes (de Francesco et al., 2018; Šilc et al., 2018). To date, studies regarding litter dynamics on dunes highlighted that reed wrack and dune vegetation act as a sink for litter (Cresta and Battisti, 2021; Andriolo et al., 2021; Ben-Haddad et al., 2023; Gallitelli et al., 2023). In detail, on the Moroccan Atlantic coast, the halophyte *Cakile maritima* L. blocked mainly food containers and ropes items (Ben-Haddad et al., 2023). The density map of marine litter in the Atlantic coast of Portugal (Andriolo et al., 2020) revealed that vegetation mostly blocked the highest number of items on the backdune (i.e., octopus pots and Styrofoam fragments) and foredune (i.e., plastic bottles, bags, papers and napkins). Styrofoam and plastic fragments were mainly found in embryo dunes, while plastic bottles and octopus pots occurred more in the fore and backdunes (Andriolo et al., 2021). In the Mediterranean Thyrrenian coast, *Carpobrotus* spp. and dune plants mainly entrapped plastic and polystyrene pieces (Gallitelli et al., 2021). Dune plants and *Phragmites australis* reedbed acted as a filter for beach litter intercepting it in the foredunes and backdunes (Gallitelli et al., 2023). Plants in the foredune blocked more plastic lids and cotton buds, while backdune vegetation entrapped mostly polystyrene pieces (Gallitelli et al., 2023).

Given that vegetation and dunes may act as a reservoir for beach litter (Andriolo et al., 2021; Gallitelli et al., 2021; Turner et al., 2021; Andriolo and Gonçalves, 2022), there might be a potential litter impact on vegetation (Menicagli et al., 2019) and on coastal processes. In this regard, Andriolo and Gonçalves (2022) proposed a first conceptual model of litter-dune dynamics, which considered dune vegetation in relation to coastal litter dynamics. Concerning the pattern of beach litter distribution, different factors are involved in the plastic retention in dune ecosystems (Corbau et al., 2023). Although the interactions between geomorphology, vegetation and marine debris on a sandy beach have been investigated with drone image analysis, the structure and role of vegetation related to litter entrapment has not yet been described (Corbau et al., 2023).

Mangroves act as barriers to landward transport of plastic litter along sheltered shorelines within the tropical or subtropical latitudes (Martin et al., 2019; Luo et al., 2021), and dune plants could play this role along sandy coasts (Andriolo et al., 2021; Gallitelli et al., 2021; Mo et al., 2021; Ben-Haddad et al., 2023; Menicagli et al., 2023; Gallitelli et al., 2023). Some studies highlighted how halo-psammophilous plants can trap litter (Andriolo et al., 2021; Gallitelli et al., 2021; Ben-Haddad et al., 2023), however little is known on their trap efficiency and on the precise distribution of litter from sea to land.

The present study aimed at investigating (i) the effect of dunal plants in entrapping beach litter (‘sink’ role), assessing differences of litter trapped between species, (ii) the litter distribution from sea to foredune, and (iii) the trapping of litter across the plant patches (i.e., edge and core areas). In this regard, we tested the hypothesis that a halo-psammophilous plant blocked litter more efficiently in the edge of the individual patch, rather than the core (inner plant) since prostrate plants could be an efficient barrier to the landward litter transport.

2. Materials and methods

2.1. Study area

The study area (Torre Flavia wetland—Natural Monument) is located on the Tyrrhenian coast and designated as a “Special Area of Conservation” (code SPA: IT6030020) (Fig. 1). In the present study, along the littoral sector, habitat types were classified in accordance with the “Habitat Directive” based on dominant and characteristic plant species (European Commission, 2007; Biondi et al., 2009; Acosta, 2021). More in particular, dunes were dominated by several halo-psammophilous plants, mainly belonging to genus *Thinopyrum, Anthemis, Echinophora, Eryngium,* and *Salsola* (Ceschin and Cancellieri, 2006; Acosta, 2021). This vegetation follows an ecological succession from sea to the beach and land. Indeed, *Cakile maritima* is found firstly near the sea on the upper beach together with *Salsola kali*, found in the drift lines (Habitat 1210). Closer to the sea, along drift lines, there is a narrow annual vegetation strip dominated by *Cakile maritima* and *Salsola kali* (Habitat 1210). This coastal dune is relatively homogeneous, with the whole study area located between 1 and 2 m a.s.l. (Regione Lazio, 1991).

Landward of the embryo dune, the EC classification describes a true mobile dune community (Habitat 2120, embryonic shifting dunes along the shoreline with *Ammophila arenaria*). There are only some species characteristics of the Habitat 2120 such as *Pancratium maritimum* and *Echinophora spinosa*. The absence of the true mobile dune habitat is probably due to the limited supply of sand from the sea, as the site is known to be undergoing erosion and human-induced trampling (Battisti et al., 2008; Santoro et al., 2012). The dune vegetation of the area can therefore be considered relative homogeneous and is represented mainly by the embryo shifting dune (Habitat 2110 of the Habitats Directive, see Santoro et al., 2012). This is the most widespread habitat, and it is characterized by the dominance of *Thinopyrum junceum* and *Anthemis maritima* (Ceschin and Cancellieri, 2006; Acosta, 2021).

2.2. Sampling protocol

On the sampling strategy used in this study (Fig. 2), we performed litter samplings on several plant species (i.e., six species, see Fig. 3) with two different morphotypes (i.e., prostrate and not-prostrate plants). Regarding litter, we sampled two size ranges (i.e., 3–5 mm and > 5 mm) in two different dune ecosystems (i.e., embryo dune and foredune belts). For each plot, we considered a small-scale distribution within the plant patch (i.e., edge and core areas). We sampled on the 26th–27th of

August 2021 with a wind speed of 4.6 m/s directed to the North-East. We reported general information on local dominant winds as well as quantitative data on their speed and direction in the sampling days. In the study area, there is normally Sirocco wind in spring-summer and Mistral in winter according to Windy App. Data on wind speed and direction were taken on Windy App (https://windy.app/it).

To individuate plants on the map, we used a systematic sampling approach where sampling plots were established at regular intervals across the study area. Each sampling plot covered a specific area, and we visually identified and marked individual plants within those plots using Google Maps coordinates. These referenced points were processed on QGIS 3.16 to produce a distribution map for each species. Each species was represented in a single map as not all species are evenly distributed along the coastal line of Torre Flavia, in fact some are present only in certain stretches, as precisely shown on the maps (Fig. 1). The map showed dots and triangles to represent the same plant species in the different habitats (i.e., embryo and foredune belts). The dots indicate plant species sampled at a distance <25 m from the sea in the embryo dune (ED), while the squares are the ones at a distance >25 m in the foredune (FD). In view of our aim on species-specific litter entrapment, this approach allowed us to analyze and compare the spatial arrangement of different plant species separately.

Halo-psammophilous species are well distributed along dunes with a natural characteristic patchy pattern. We considered a 'patch' to be a halo-psammophilous plant unit separated by at least 10 cm from another unit, following a patch-matrix approach traditionally used in landscape ecology (Forman and Godron, 1981). Plastic litter was collected in plots placed both at each plant patch and in a neighbouring unvegetated plot of comparable size (i.e., on sand matrix; control plot), following the methods used for *Carpobrotus* spp. in Gallitelli et al. (2021) and shown in Fig. 2. The sampling plot for each individual plant comprised its full height and a circular area of about 0.5 m radius around the plant. This radius, measured with a meter measuring tape, was drawn from the main stem of the plant. In this way, the core of the plant was identified by representing the centre of the surveyed circle. It should be noted that plants were comparable in size (radius of 0.5 m about) thus generally each plot was a circle of 1 m^2. A random control plot was set adjacent to each plant plot. Overall, a total of 180 plant plots with plants ($n = 30$ for each species) and 180 unvegetated plots for control were sampled. We accounted for a total of six species well-distributed along dunal and coastal habitats: *Echinophora spinosa*, *Limbarda crithmoides*, *Anthemis maritima*, *Pancratium maritimum*, *Thinopyrum junceum,* and *Salsola kali.* Species selection was made on the basis of their relative occurrence, being subsequently classified in prostrate (i.e., *E. spinosa*, *S. kali*, and *A. maritima*) vs. non-prostrate plants (i.e., *P. maritimum*, *T. junceum,* and *L. crithmoides*). According to Lavorel et al. (1997) and Cornelissen et al. (2003), prostrate plants were those herbaceous plants with leaves concentrated very close to the soil surface.

We consider micro-litter (MI) and macro-litter (MA) to be litter items smaller and larger than 0.5 cm, respectively (see Galgani et al., 2013; GESAMP, 2019; Gallitelli and Scalici, 2022). We used visual census for both micro- and macro-litter. In detail, the lower size limit for micro-litter was 3 mm in order to carry out a proper visual account of small items (Galgani et al., 2013). While *visual census* was used to spot macrolitter, the size of smaller items was checked with a calliper ±1 mm (following Martellini et al., 2018). Litter items were placed in sterile containers to be counted and classified. We followed the Marine Strategy Directive for classifying the beach litter according to Galgani et al.

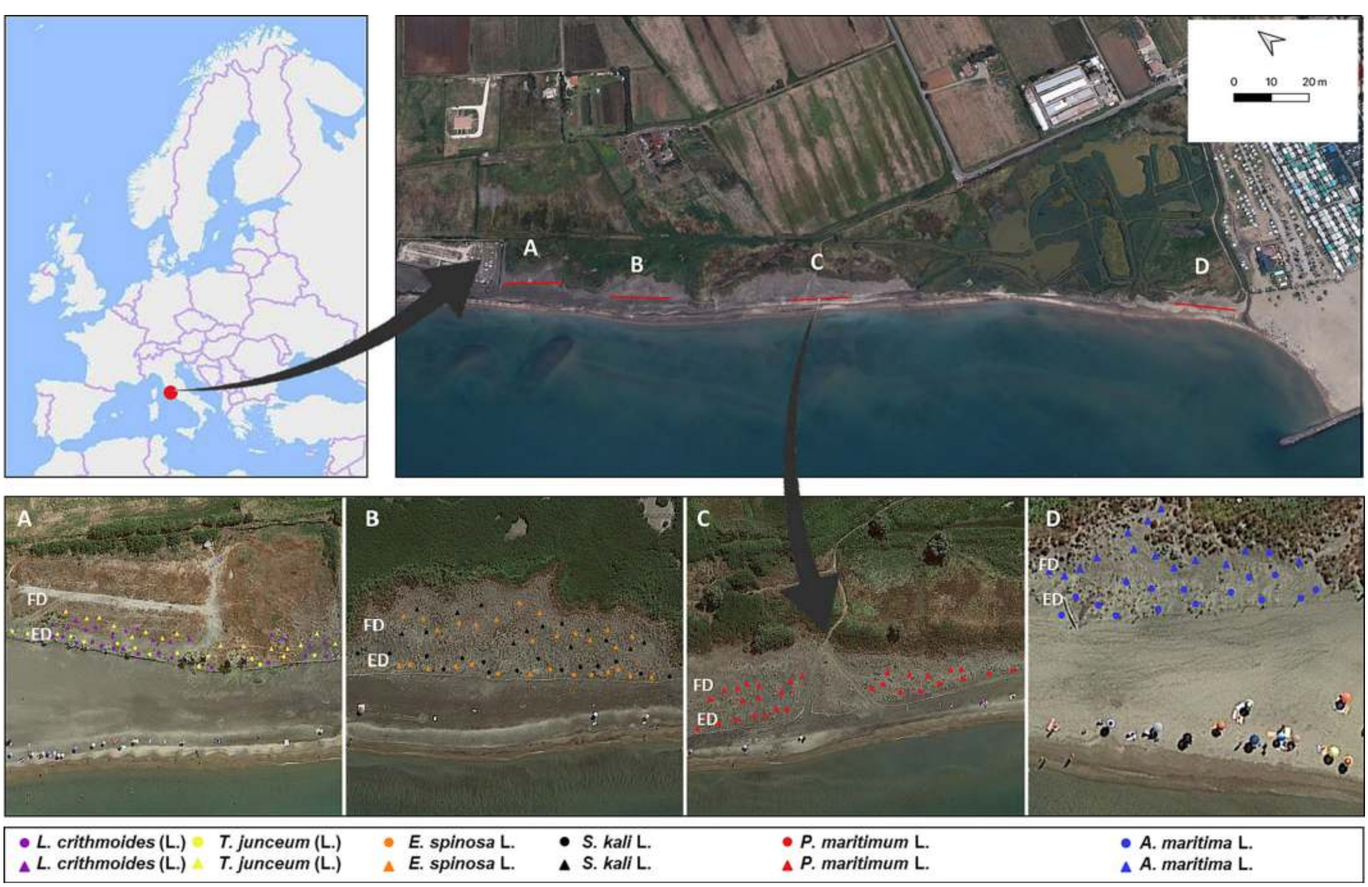

Fig. 1. The study area reports the sampled six species along dune habitats. The dots and triangles represent the same plant species in the different habitats (i.e., embryo and foredune belts). The dots indicate plant species sampled at a distance <25 m from the sea in the embryo dune (ED), while the squares are the ones at a distance >25 m in the foredune (FD). The map of Europe has been taken by © OpenStreetMap. All the images were processed with QGIS 3.16.

(2013). Since the distance from the seashore may affect the litter dynamics and related pattern of deposition (Cresta and Battisti, 2021), we investigated the distribution of litter cross-shore (i.e., embryo dune and foredune), using two different distances from the sea (i.e., embryo dune: distance<25 m: 15 plots and foredune belts; d > 25 m: 15 plots). We chose this 25-m habitat segmentation as embryo dune and foredune were characterized by different plant coverage. Regarding the habitat and species selection, in the study area, on embryo dune and foredune there are species that efficiently block plastic litter, from previous research. Precisely, *Carpobrotus* spp., *Phragmites australis* L. reedbed, *Anthemis maritima* L., *Echinophora spinosa* L., *Elymus (Thynopyrum) arenarius* L. (see Gallitelli et al., 2021; Cresta and Battisti, 2021; Gallitelli et al., 2023). As in previous works the effect of entrapping plastics has been studied on the entire community and in separate habitats (i.e., embryo dune or foredune belts), now the role of single species that dominated the dune community has been analysed species by species and with habitat comparison. The part near the sea (<25 m), hereafter embryo dune (i.e., ED), are mainly exposed to wave and meteo-climatic conditions that brings the sand to form the incipient dunes. Then, the part far from the sea (>25 m), hereafter foredune (i.e., FD), is characterized by new formed dunes inhabited by dune species. Moreover, as previous studies pointed out that plants patches efficiently trapped litter and the dune ecosystems is highly composed by patches (see Gallitelli et al., 2021; Andriolo et al., 2021), to better understand litter dynamics on dunes, it is crucial to investigate which part of the patch is retaining more plastics. Given that the external part of the patch (i.e., edge area) could be more active in litter transport and dynamics, we evaluated and compared the quantity of litter in the edge and core areas. Thus, any sampled patch was divided into an internal section (core area: CORE) and a peripheral margin (edge area: EDGE), where the total litter items was the sum of both sections (total, TOTL = EDGE + CORE). While the CORE of the plot was identified by representing the centre of the surveyed circle, the EDGE area was considered sampling litter in the 5 cm nearest to the external part of the circle plot.

2.3. Data analysis

2.3.1. Sink effect in dunal plants

To compare the litter blocked in plants with the one found in control plots, a Wilcoxon test was performed. Among plants, to test which species was more efficient in trapping litter, a Wilcoxon matched-pairs signed rank test was carried out (Dytham, 2011). The Wilcoxon test was used as nonparametric method to compare matched subjects (i.e., plants vs. control). In detail, this test compares the median of a set of numbers against a hypothetical median (GraphPad Prism version 8.0.1; Dytham, 2011). Moreover, to investigate the trap efficiency for litter type occurring in the dune plants, an ordinary one-way ANOVA was conducted. The ANOVA test has been used as data were normally distributed and the test compares the mean of the litter type groups (GraphPad Prism version 8.0.1; Dytham, 2011).

2.3.2. Distribution of litter across the shore

Litter items were analysed in a matrix with species, litter typology and distance from sea (assuming an effect due to sea distance) both for plant plots and control plots.

To describe about the sea-land gradient, the percentage of litter trapped by any plant was calculated as number of items divided by total items for each species. Additionally, to assess a significant litter accumulation in plant species in relation to the distance to sea, a $\chi 2$ test was calculated among all the species and singularly for each species.

2.3.3. Is litter accumulated more at the edge area of plant patches?

To investigate whether beach litter is mainly retained at the edge, the patch core or in the sandy area, a Kruskal-Wallis test (H′) for equal medians was performed comparing averaged values (Dytham, 2011). In this case, the Kruskal-Wallis test has been used as nonparametric test to compare three unpaired or unmatched groups (Dytham, 2011). After finding a significant difference in the three groups tested by Kruskal-Wallis test, a Dunn's test can be used to spot which specific pairwise

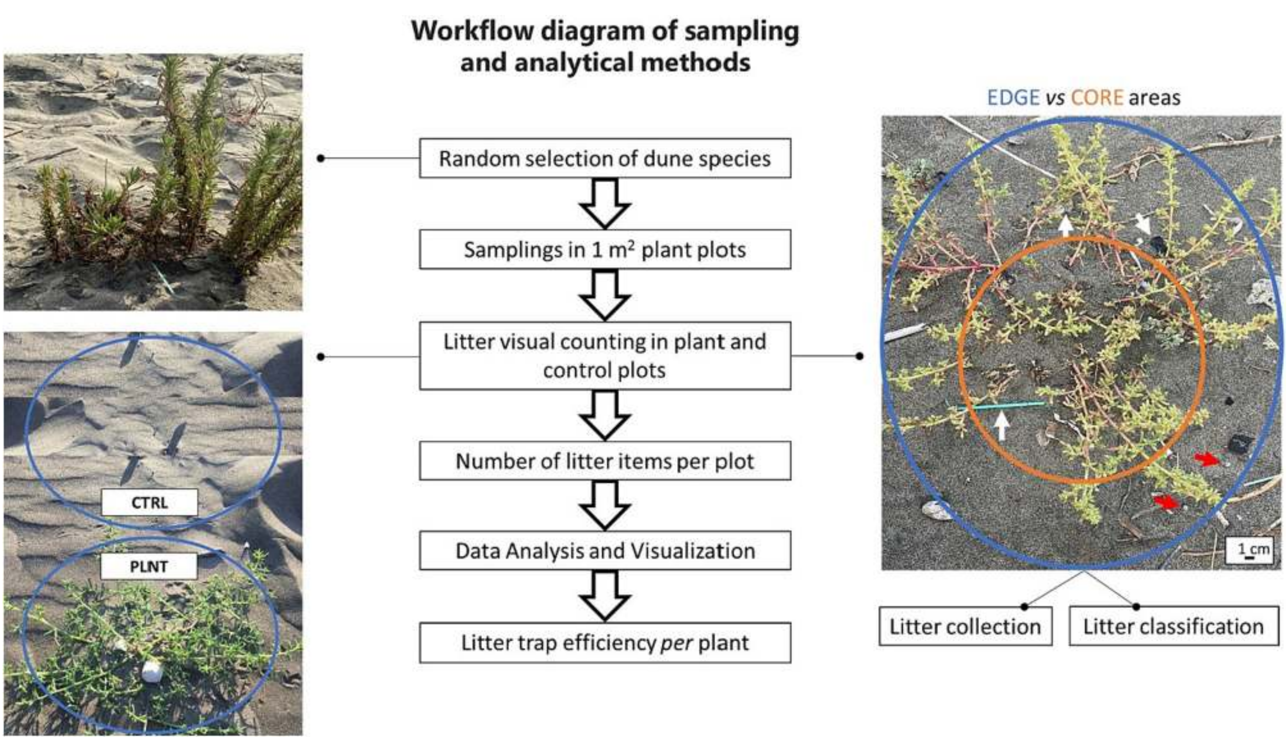

Fig. 2. Workflow diagram of sampling design for litter in dune vegetation. After a selection of dune species, circular plots were applied to sample dune plants (PLNT) and relative control area (CTRL). For each plant plot, the blue circle indicates the EDGE area while the orange one indicates the CORE area. The white arrows represent macrolitter items (MA) while red arrows are large microlitter items (MI). The scale is reported as 1 cm value. Then, the litter is collected to be quantified and to perform data analysis to obtain litter trap efficiency per plant.

are significant from the others (i.e., EDGE vs CORE, CORE vs. SAND, and EDGE vs SAND). Thus, an uncorrected Dunn's post hoc was carried out (Dytham, 2011) to test a significative difference among groups (EDGE, CORE, and SAND).

To perform the analyses, we used GraphPad Prism version 8.0.1, GraphPad Software, ww.graphpad.com. Alpha level was set at 0.05.

3. Results

3.1. Dune plant community sink effect

Overall, we sampled 670 litter items in dune plants (Fig. 3) and 48 items in unvegetated plots. Microlitter item in plants accounted for 214 items (31.9 %), while macrolitter items were 456 (68.1 %). Dune plants (PLNT) entrapped significantly more litter than control plots (SAND) ($W = 21.0$, $p < 0.05$, Figs. 3 and 4a). *A. maritima* was more significantly efficient in capturing litter rather than the other plants (PLNT = 172 items, 25.7 %), while *E. spinosa* was the less efficient (PLNT = 67 items, 10.0 %) ($W = -21.0$, $p < 0.05$; Fig. 4b). Trap efficiency decreased in not prostrate plants (i.e., maximum in *A. maritima,* 25.7 % and minimum in *L. crithmoides* and *E. spinosa*, 10.1 % and 10.0 % of trap efficiency, respectively). Regarding the litter types, polystyrene pieces and plastic items are the most occurring types in plants (52.9 % and 32.8 %). Concerning polystyrene pieces, *P. maritimum* is the best trapper (13.7 %), while *L. crithmoides* is the worst (2.5 %). Regarding plastic items, *A. maritima* trapped most efficiently plastic items (10.7 %), while *E. spinosa* trapped them less efficiently (1.9 %) ($F_{(2,10)} = 8.833$, $p = 0.006$).

3.2. Distribution of litter across the shore

Overall, *E. spinosa*, *L. crithmoides*, *A. maritima* and *P. maritimum* showed more litter in the ED patches near the sea, while *T. junceum* and *S. kali* accumulated more litter near the FD (Fig. 5). Among all the species there is a significant difference ($\chi2$ (5) $=55.6$, $p < 0.0001$). In detail, *E. spinosa*, *A. maritima*, and *T. junceum* showed a significant difference ($p < 0.05$).

Frequency of litter items retained by dune plant species across the shore was shown in Fig. 6. Differences between the ED and FD were apparent only for *E. spinosa* and *T. junceum*. *E. spinosa* trapped litter mainly in the embryo dune belt close to the sea, while *T. junceum* trapped in the foredune belt furthest from the sea (Fig. 6).

Regarding the type of litter (see Fig. 6B, Fig. 8), *P. maritimum, A. maritima, L.* and *E. spinosa* entrapped mostly polystyrene pieces in ED habitats, while *S. kali* and blocked polystyrene pieces in the FD. Moreover, while *A. maritima*, *L. crithmoides*, and *E. spinosa* blocked plastic items in the ED, *P. maritimum*, *S. kali*, and entrapped them mostly in the FD. Among all dune plants, *P. maritimum* retained most of polystyrene pieces in ED while *T. junceum* polystyrene pieces in the FD (8.5 % and 5.9 %, respectively).

3.3. Is litter accumulated more at the edge area of plant patches?

Regardless of being near or far from the sea (i.e., ED or FD), we found that the edge of the plant patches captured more plastics than the core area (EDGE, $n = 501$, 69.1 % vs CORE, $n = 169$, 23.5 %). In the control area (SAND) a total of 48 items were found (6.7 % of total litter). Moreover, regarding the trapped litter, there is a significant difference among EDGE, CORE and SAND ($H = 14.36$, $p < 0.05$). Particularly, Dunn's post hoc revealed that EDGE and SAND as well as CORE and SAND were significantly different ($p < 0.05$) revealing that EDGE and CORE areas entrapped more plastics rather than SAND, respectively.

Both the edge and core zones entrapped mainly macrolitter. Specifically, most of the litter retained in the edge was composed by

Fig. 3. Litter entrapment by the six dune species. The morphotype «prostrate» is represented by *E. spinosa, S. kali,* and *A. maritima* (A, B, and C) and «non-prostrate» plants with *P. maritimum, T. junceum,* and *L. crithmoides* (D, E, and F). The black arrows indicate the plastic items trapped by plants.

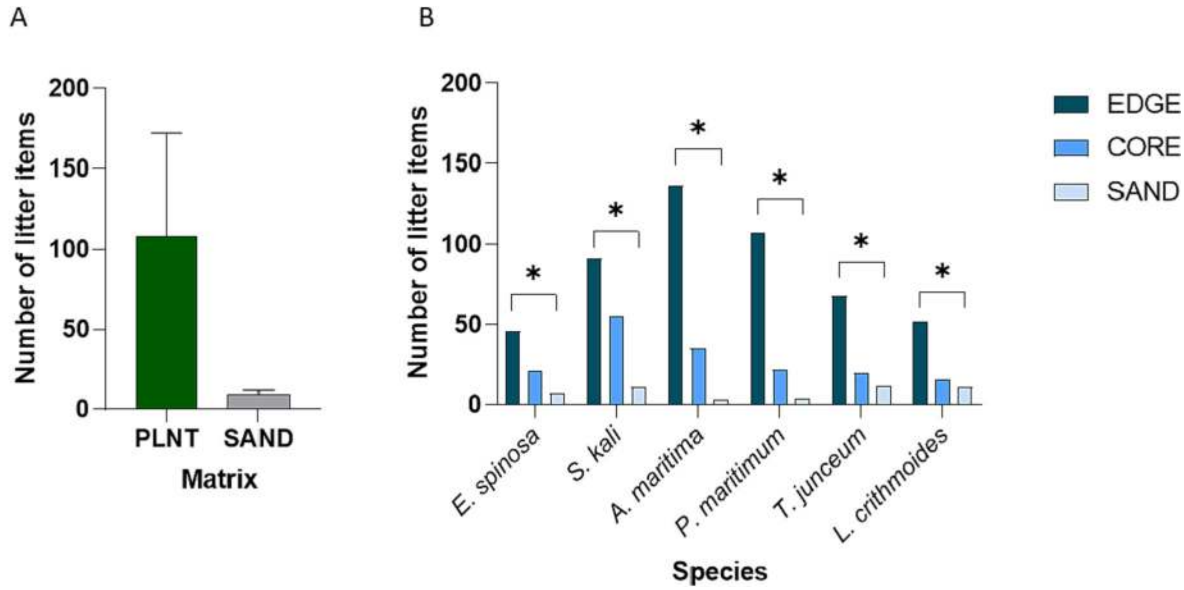

Fig. 4. (A) Litter retention (n. litter/plant) in vegetated and unvegetated plots. Median with 95 % CI of number of retained litter. PLNT = plant, SAND = sand (control). (B) Litter retention per plant species. EDGE = edge area, CORE = core area, SAND = sand (control). The asterisks indicate the significance of results ($p < 0.05$). The litter considered the sum of micro- and macro-litter. *E. spinosa*, *S. kali*, and *A. maritima* are the prostrate plants, while *P. maritimum*, *T. junceum*, and *L. crithmoides* non-prostrate plants.

macrolitter ($n = 347$, 68.9 %), while microlitter occurred for 31.1 % ($n = 156$). Macrolitter also dominated in the core area ($n = 119$, 67.2 %) against microlitter ($n = 58$, 32.8 %).

Among the prostrate plants, *S. kali* captured plastics more efficiently in the FD, while *A. maritima* and *E. spinosa* in the ED (Table 1, Fig. 7). For non-prostrate plants, *P. maritimum* entrapped mostly MI in the core area, while *L. crithmoides* retained more efficiently MI in the patch core in the ED and in the edge in the FD, and *T. junceum* entrapped mostly MA in the core area in the ED and in the edge area in the FD (Table 1; Fig. 7). *A. maritima* captured more efficiently MA in the edge (both in ED and FD areas) as well as *P. maritimum*, *L. crithmoides*, and *S. kali* (Fig. 7).

Regarding the types of litter entrapped by plants (see Fig. 8), among all dune plants, *P. maritimum* retained most of polystyrene pieces, while *A. maritima* blocked mostly plastic items (10.8 % and 9.1 %, respectively). Except for *S. kali*, polystyrene and plastic pieces were mostly trapped in the EDGE area rather the CORE area (means of 27.8 and 9.5, respectively). Contrarily, *S. kali* retained polystyrene pieces similarly in the two areas and more plastic items in the EDGE than in the core (90.0 % and 10.0 %, respectively).

4. Discussion

Previous studies reported the capacity of single dune species to retain beach litter (Gallitelli et al., 2021; Andriolo et al., 2021; Battisti et al., 2023b). The present study analyses for the first time the capture of litter by dune vegetation at a multi-species level, accounting for their morphological structure. Our analysis showed that psammophilous plants mainly retained macrolitter, acting as a common sink for anthropogenic litter in the sandy shorelines. Secondly, we found significant differences between species across the dune zone. *E. spinosa*, *A. maritima* and *T. junceum* generally trapped litter in the foredune area, while *L. crithmoides*, *P. maritimum*, and *S. kali* trapped litter similarly throughout the dune area. Lastly, our results highlighted how beach litter was accumulated at the edge of the vegetation patches rather than in the core, highlighting the 'Plant-edge litter effect'.

Among the sampled species, *A. maritima* was the most efficient in trapping litter, while *E. spinosa* were the less efficient. Although further studies are needed, our results pointed out that *A. maritima* and *E. spinosa* show different trapping efficiency for beach litter. This could be due to their morphological structure. *A. maritima* has a full basal agglomerate of leaves that may entangle litter efficiently, while *E. spinosa* shows spiny leaves able to trap other litter categories (e.g., different in size and typology).

Few researches addressed the distribution of litter into the vegetated dunes (Poeta et al., 2015; de Francesco et al., 2018; Gonçalves et al., 2020; Mo et al., 2021; Battisti et al., 2023b; Corbau et al., 2023). Of particular note are the studies by Cresta and Battisti (2021) and Gallitelli et al. (2023) on backdune reedbeds. These studies found significant foredune-backdune differences in the trapping capacity of plant species. All plants located in the embryo dune belt (i.e., ED, near the sea) retained more litter that those in the foredune (i.e., FD, far from the sea). Based on the present results, we propose that much of the microlitter likely crosses the dune vegetation barrier without being trapped, while macro-litter is more susceptible of being retained due to their larger size. This hypothesis would be also consistent with results reported by other authors (Andriolo et al., 2021; Cresta and Battisti, 2021; Gallitelli et al., 2023). Moreover, plants in the foredunes would trap smaller litter than the *Phragmites australis* reeds in the backdunes (Cresta and Battisti, 2021; Gallitelli et al., 2023). More specifically, our results highlighted that *E. spinosa*, *L. crithmoides*, *A. maritima*, and *P. maritimum* accumulated significantly more macrolitter in the patches located in the ED than in the FD. No differences were found between ED and FD for *T. junceum* and *S. kali*. The trapping capacity of dune species is probably related to plant structure, i.e., prostrate vs. non-prostrate plants, but also the shape of leaves and the occurrence of particular branches or roots (see Gallitelli et al., 2021; Ben-Haddad et al., 2023).

At small scale (within the individual vegetation patches), we found that beach litter was entrapped mainly at the edge (approx. 70 %) in comparison with the core area. Gallitelli et al. (2021) also reported that prostrate plants (i.e., *Carpobrotus* spp.) accumulate little litter within the core of the patch. The role of the *Carpobrotus* spp. in trapping litter was further confirmed by Calderisi et al. (2023). In both studies, *Carpobrotus* spp. entrapped efficiently both plastic pieces and polystyrene pieces. Although *Carpobrotus* spp. is a concerning alien species for the Mediterranean dune ecosystems (González-Moreno et al., 2017), it plays a role in entrapping beach litter and, consequently, could be useful during clean-up activities (Gallitelli et al., 2021; Calderisi et al., 2023).

According to our results, litter accumulation in the core of the

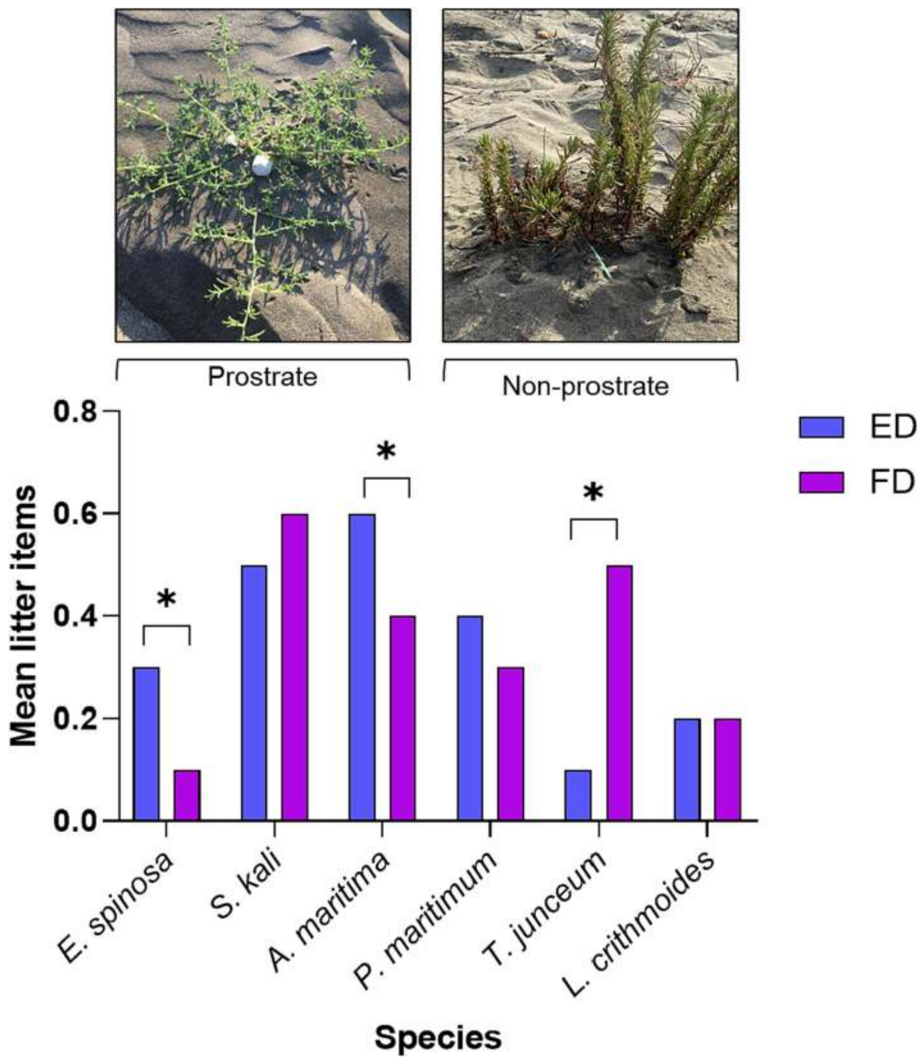

Fig. 5. Litter accumulation in plant species (mean litter/plant) in relation to the dune habitat with distance to sea. ED is the embryo dune habitat nearby the sea, while FD is the foredune belts habitat far from the sea. Bars show mean standard error.

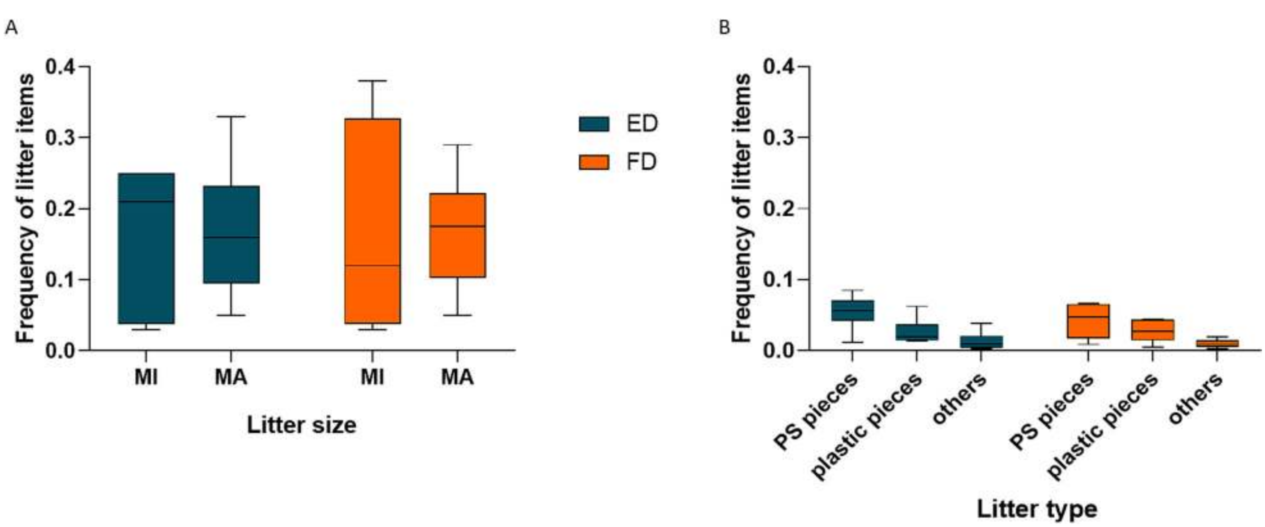

Fig. 6. Frequency of litter items related to (A) litter size and (B) type retained by dune plant species across the shore. ED is the embryo dune habitat nearby the sea, while FD is the foredune belts habitat far from the sea. MI = microlitter, MA = macrolitter.

Table 1
Micro- and macro-litter frequencies (number of litter items per species on total litter entrapped by plants) for EDGE and CORE in relation to dune habitat (e.g., embryo dune, ED and foredune, FD). EDGE = edge area, CORE = core area. MI = microlitter, MA = macrolitter.

Species	Litter frequency (ED)				Litter frequency (FD)				Total
	EDGE		CORE		EDGE		CORE		
	MI	MA	MI	MA	MI	MA	MI	MA	
E. spinosa	3.24	2.35	0.15	1.62	0.29	0.88	0.59	0.74	9.86
T. junceum	0.74	1.62	0.00	0.15	3.09	4.56	1.18	1.91	13.25
L. crithmoides	0.44	3.53	0.15	1.62	0.44	3.38	0.15	0.44	10.15
S. kali	2.21	4.26	2.21	1.62	3.09	3.82	2.21	2.06	21.48
A. maritima	3.68	8.38	0.74	3.24	0.44	7.79	0.00	1.76	26.03
P. maritimum	3.09	6.18	0.88	0.88	2.21	4.26	0.29	1.47	19.26
Total	13.4	26.3	4.10	9.10	9.60	24.7	4.40	8.40	100.00

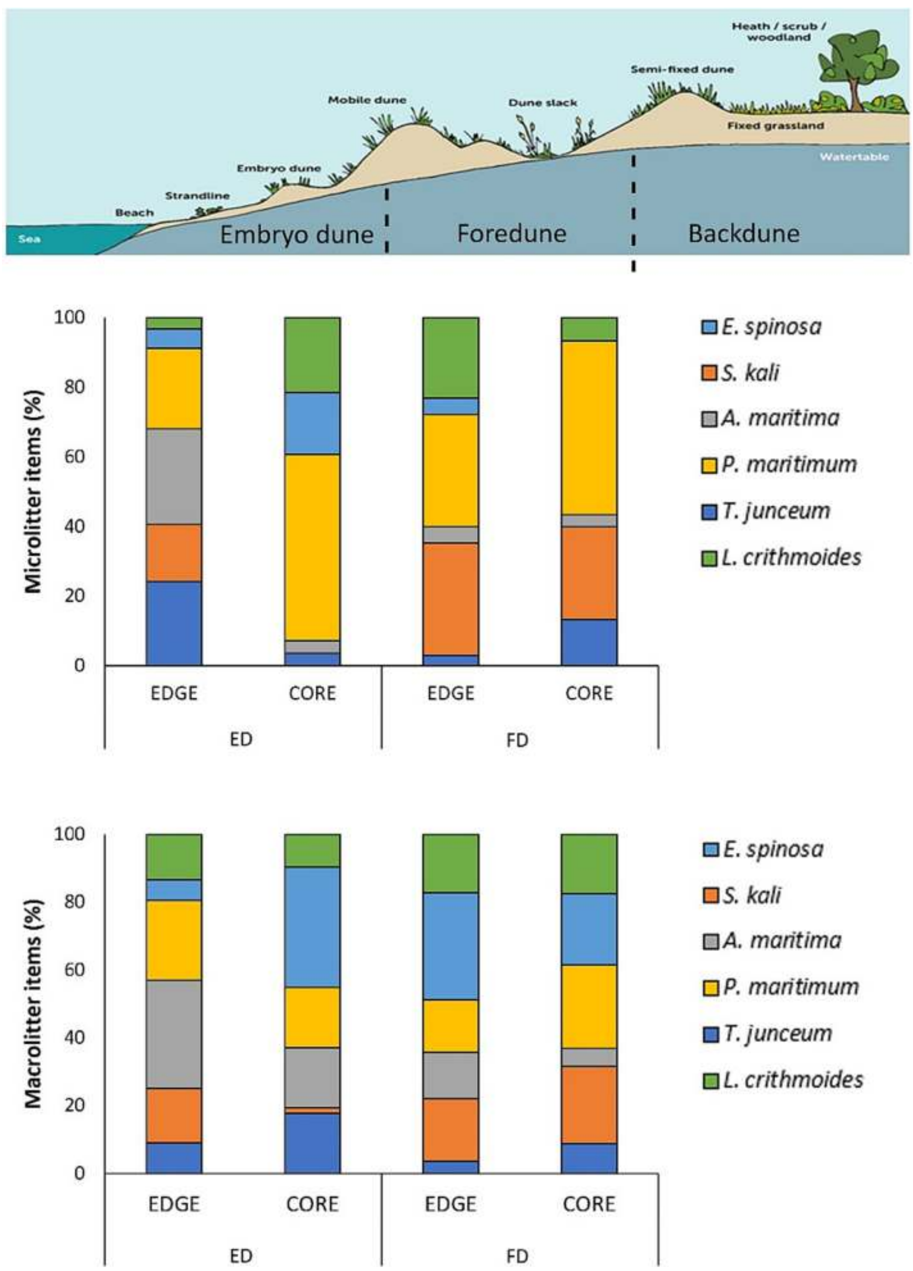

Fig. 7. Relative frequencies (% in abundance) of litter entrapped by dune plants in the embryo dune (ED) and foredune (FD) areas. EDGE = edge area, CORE = core area, MI = microlitter, MA = macrolitter. The plant transect is taken on https://dynamicdunescapes.co.uk/about-sand-dunes/dune-lifecycle/.

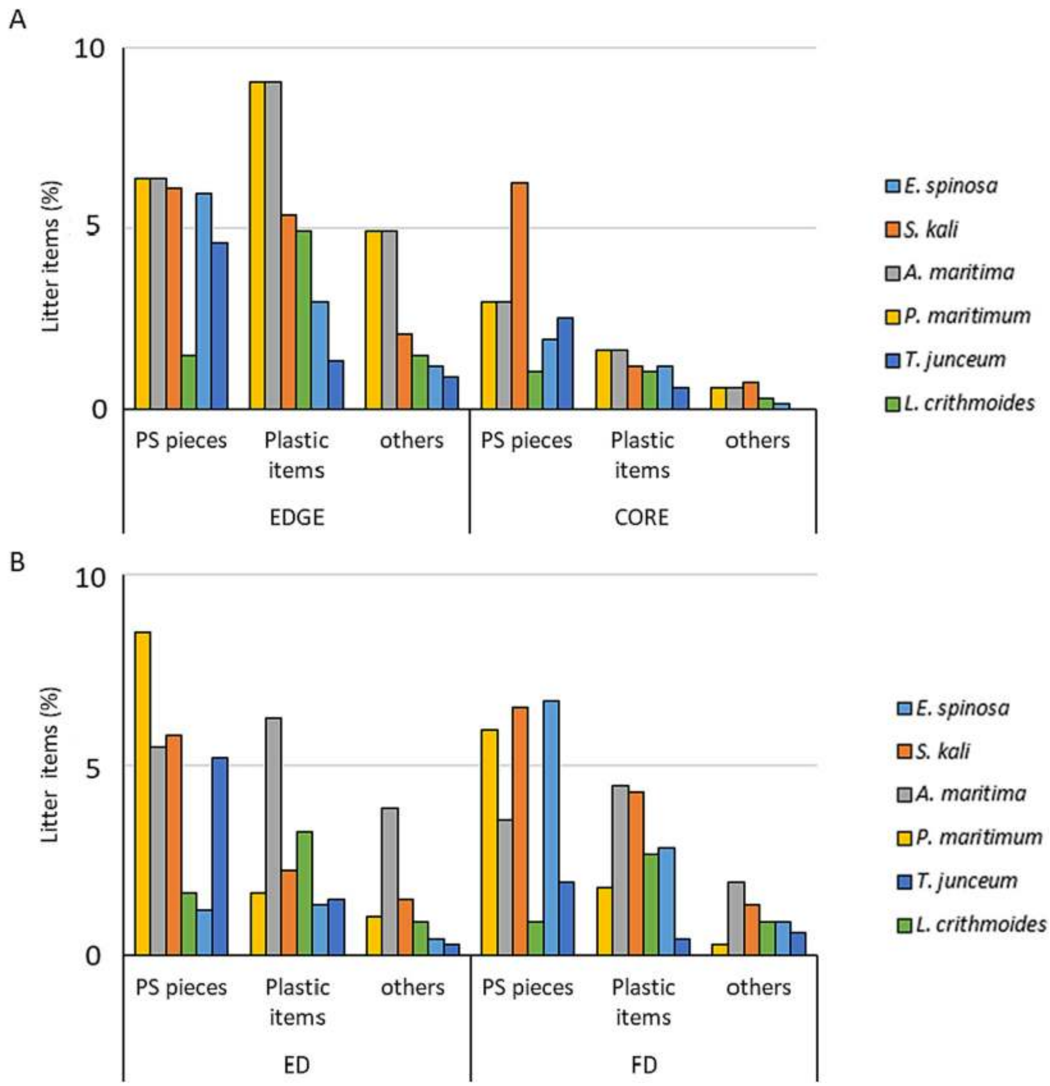

Fig. 8. Frequency of litter types (%) for the six species in small scale (i.e., edge and core areas, panel A) and different habitat (i.e., embryo dune and foredune belts, ED and FD respectively, panel B).

vegetation patch is strongly dependent on whether it made up by a prostrate or non-prostrate plant (e.g., *P. maritimum, T. junceum,* and *L. crithmoides*). Litter items remain entrapped by the plant structure. Litter still in the core will remain stuck in the core, whereas most of the litter coming from outside remains in the edge part, without penetrating the core. In this perspective, structure and size of plants are key in understanding the spatio-temporal pattern of litter entrapment.

The above-described 'litter edge effect' for the dune vegetation patches (i.e., litter retention into the patch edge) could imply effects on the animal species inhabiting or foraging around the dunal plants, as invertebrates; reptiles; plover birds. Litter accumulated in the vegetation patch may act as threat (e.g., entrapping individuals; Romiti et al., 2021; Battisti et al., 2023a) or opportunity (shelter or substrate for plants: Poeta et al., 2015). We should consider that litter can act as a stressor for plants decreasing native plant survival and growth (Menicagli et al., 2023). Moreover, plastic debris can increase the spread of invasive plants (Menicagli et al., 2023), posing an additional risk to the dune ecosystem.

In addition to the macro-structure (i.e., life form) of the vegetation patches, the complexity of the leaf form might also influence the plant trapping ability. Although dune plant structure is of recent investigation (Gallitelli et al., 2021; Ben-Haddad et al., 2023), it should be a central factor for litter dynamics on dunes. Here we found that the more articulated and complex the structure of plant is, as in *A. maritima*, the more the plant can trap even small plastics. On the other hand, not prostrate plants allow litter to pass more easily into the core area (as in *T. junceum*). In literature, Gallitelli et al. (2021) pointed out that the tridimensionality of *Carpobrotus* spp. and dune plant structure is key to entrap plastic and polystyrene pieces, while Ben-Haddad et al. (2023) highlighted that the halophyte *Cakile maritima* L. entrapped mostly food containers and ropes items. Another study focusing on a single species approach pointed out that *S. kali* plants trap polystyrene and plastic items (Battisti et al., 2023b), mostly due to the branched structure of the plant, characterized by fleshy and prickly leaves and a small thorn at the apex. Thus, plant structure is a driving force in plant retention of litter, however it might depend also on litter material found in the surrounding area. Indeed, litter in plants reflects litter occurring in the environment adjacent to the sampling area. In this case, a land use analysis could better allow to understand the source and quantity of certain litter types in the plant plots (Andriolo et al., 2021).

A. maritima blocked litter mainly in the ED patches near the sea while *S. kali* in the FD far from the sea. Previous reports highlighted that vegetation mostly blocked items on the backdune (i.e., styrofoam fragments) and foredune (i.e., plastic bottles, bags, papers and napkins) (see Andriolo et al., 2021; Gallitelli et al., 2023). To explore the effect of the type of litter (e.g., shape, size, weight) on its likelihood of retention across the dune field, we merged data on litter size and type. With regards to prostrate plants, *S. kali* blocked plastics more efficiently in the FD, while *A. maritima* and *E. spinosa* in the edge of the ED (Table 1, Fig. 6). For not-prostrate plants, *T. junceum* retained more MA, while *P. maritimum* and *L. crithmoides* captured more MI, mainly in the core area. Regarding the litter typology, polystyrene and plastic pieces accumulated more at the edge of plant patches. The fact that polystyrene and plastic pieces were mainly trapped in the edge of the vegetation patches would facilitate its redistribution in the dune ecosystem. Wind and high waves could move litter along coastal ecosystems until it becomes trapped again or goes back to the sea (Andriolo et al., 2020; Turner et al., 2021; see Andriolo and Gonçalves, 2022 for litter-dune dynamics).

In attempt to advance our understanding of the retention and release of litter in relation to dune plants, here we propose a preliminary explanatory hypothesis for the small-scale dynamics of micro and macrolitter across the Mediterranean dune environments. Wind flow is expected to redistribute both micro and light macrolitter, particularly the light film-type and foamed plastic items (according to Andriolo and Gonçalves, 2022). A major difference in the wind-induced transport of these two litter size fractions could be related in how micro or macrolitter are trapped by vegetation patches. Macrolitter is more likely to be entangled and trapped by the dune plants, while micro litter is more linked to dune sand dynamics, being more easily buried and moved up and down with the sand. Interestingly, a comparable idea was proposed for the coastal underwater dynamics of non-floating macro- and microlitter in relation to the seagrass beds commonly bordering the Mediterranean shores, although in this case with coastal currents as a driver of transport and *Posidonia* meadows as litter sink (Navarrete-Fernández et al., 2022). More targeted studies, especially involving sampling of microplastics buried with the sand, are needed to test the hypothesis drawn from our study.

Our findings could be of great usefulness in management, considering the ecosystem service provided by plants in retaining litter. Indeed, considering plants as a hotspot for litter and plastic, the present results provide valuable information on plastic accumulation areas, useful for improving the effectiveness of litter pollution mitigation plans in shorelines and coastal ecosystems (Battisti et al., 2020c).

Future research could focus on how to conduct better monitoring of litter and plastic pollution. Understanding the pattern of movement and recapture of litter from a patch to patch could help to know potential hotspot areas along the dune systems, of particular interest for targeting clean-ups efforts. Advances in dune litter monitoring would provide a consistent basis for removal actions and mitigate its multiple effects on sandy shore ecosystems. In this regard, a few studies pointed out as UAVs (Unmanned Aerial Vehicles) and multispectral satellite imagery could be used to detect macrolitter on beaches (Andriolo et al., 2021; Balsi et al., 2021; Gonçalves et al., 2022). This approach still needs to be consolidated before it can be widely used, but it has a promising potential to assist field samplings. Moreover, new research should highlight the impact of dune morphology and vegetation volume on litter distribution. As coastal dunes result from complex interactions among aeolian processes, sediment transport, nearshore hydrodynamics and dune vegetation, a characterization of dunes with a digital surface model (DMS) and an orthomosaic will allow to better understand which factors influence litter dynamics on beaches. Our study should address some important limitations. For instance, a more accurate sampling of microlitter should be provided if the study aim focus on it - particularly towards sizes smaller than 1 mm, otherwise it should provide underestimation of the particles. Then, there could be the need to incorporate fine-scale mapping (e.g., DSM, orthomosaic) to address the complex interplay of driving factors controlling the litter dynamics in coastal dunes. Moreover, it would allow replication of study in dune systems with a different structure as well as to address other study scales – with the aim of standardising methodology and comparing results to draw higher insights and conclusions.

5. Conclusions

Given the threat posed by marine litter to sandy coastal ecosystems and the fact that dune vegetation represents a trap for beach litter, we should pay more attention to dune ecosystems to combat coastal litter pollution. Although the present study is limited to a small location within central Italy, our data provide clear evidence of widespread litter capture by dune vegetation, with inter-specific differences related to plant morphology. As *A. maritima* and *S. kali* entrapped respectively more litter in embryo and foredune habitats, these species could be used to monitor and recover litter. In this light, our findings provide further insight into the role of dune plants in the beach litter dynamics, suppling useful information for beach clean-up actions. We encourage further research to extend monitoring to larger scales in order to provide much-needed information on the ecosystem service of macroplastic litter trapping by dune plants.

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CRediT authorship contribution statement

Luca Gallitelli: Conceptualization, Investigation, Methodology, Data curation and formal analysis, writing original draft-reviewing and editing, validation. Martina D'Agostino: Investigation, Validation, Software. Corrado Battisti: Conceptualization, Methodology, Formal Analysis, writing original draft- reviewing and editing, software, validation, resources. Andrès Cozàr: Writing - Review & Editing, validation. Massimiliano Scalici: Writing- Reviewing and Editing, supervision, validation.

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

All data are present in the manuscript and Supplementary Materials.

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