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Posidonia oceanica banquette accumulations in southern Catalonia: management approaches and key parameters for coastal protection

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Seagrass banquettes, formed primarily by *Posidonia oceanica*, play a critical role in coastal protection and sediment dynamics. However, due to their perceived negative impact on seaside tourism, local authorities frequently remove these accumulations using heavy machinery, contributing to beach erosion. This study surveyed a 100 km stretch of the southern Catalan coastline to map the spatial distribution of *Posidonia oceanica* banquettes and to investigate their relationship with adjacent submerged seagrass meadows. The results indicate that banquette development is most prevalent in meadows with a depth of less than 5 m, under local wave conditions with significant wave heights ranging from 0.4 to 0.8 m. Pixavaques Beach was selected as a case study to evaluate the physical characteristics and ecological functions of banquettes. Granulometric and permeability analyses were conducted on sand and banquette samples, alongside *in situ* penetration resistance measurements. The results indicate that banquettes located near the shoreline accumulate around 12 times less sediment than those located further inland, primarily due to their continuous exposure to wave action, which produces a natural washing and removal of sediments. The mean permeability values of the banquette were 16.41 cms^{-1} in the zones closest to the shoreline and 0.32 cms^{-1} at a distance of 1.5 m inland. The values obtained for these samples were higher than those measured in bare sand (0.05 cms^{-1}). The maximum *in situ* penetration resistance values were recorded as 1.84 MPa in bare sand and 1.68 MPa in the banquettes. The highest values measured within the banquettes indicate zones of greater sediment accumulation. Additionally, the artificial nourishment implemented to counteract erosion from banquette removal has led to increased grain size and steeper beach profiles. These findings highlight the protective function of banquettes and support alternative, sustainable management strategies, such as repositioning or partial retention, that balance ecological integrity with the demands of coastal tourism.

KEYWORDS

Posidonia oceanica **accumulation, clean beach management, sediments trapping, banquette parameters, beach erosion, sandy beaches, Mediterranean sea**

1 Introduction

Seagrass meadows cover an estimated area of up to 600,000 km^2 (Duarte et al., 2010) in shallow coastal waters worldwide, excluding the Antarctic coast (Hemminga and Duarte, 2000). Among these, *Posidonia oceanica* stands out as an endemic seagrass species of the Mediterranean Sea, thriving across a range of clear water depths, from shallow coastal areas to depths of up to 60 m, according to light conditions (Ondiviela et al., 2014). In particular, its distribution extends over approximately 12,250 km^2, covering coastal regions from Spain to Lebanon (Telesca et al., 2015). *Posidonia oceanica* plays a vital role in marine ecosystems, contributing to biodiversity and productivity (Enríquez et al., 1993). These meadows represent the climax ecosystem of the infralittoral bottoms of the Mediterranean basin (Mazzella et al., 1992), providing long-term carbon sequestration (Nakakuni et al., 2021; Duarte et al., 2005), supporting high biodiversity (Jinks et al., 2019; Mazarrasa et al., 2018), and providing essential habitats for numerous marine species (Gartner et al., 2013). Furthermore, seagrass meadows are essential for coastal dynamics, influencing sediment stabilisation (Infantes et al., 2022). Field and laboratory studies have demonstrated a significant decrease in wave height (Astudillo et al., 2022; Manca et al., 2012), change in wave velocities (Barcelona et al., 2021b; Koftis et al., 2013; Pujol et al., 2013), modifications in sediment transport (Astudillo-Gutierrez et al., 2024b; Barcelona et al., 2021a; Vu et al., 2017; Gacia and Duarte, 2001), and reduction of beach erosion (Astudillo-Gutierrez et al., 2024a; Boudouresque et al., 2006).

The seagrass meadows support highly productive ecosystems (Hemminga and Duarte, 2000), with most of the biomass production coming from the decomposition of the leaves of the meadows. This decomposed organic matter subsequently either enriches adjacent ecosystems or accumulates on proximate shorelines (Jinks et al., 2019; Mazarrasa et al., 2018). *Posidonia oceanica* typically sheds some of its leaves along with its fruits (Wittmann, 1984), which are then transported by waves to the shore, forming early isolated accumulations along the beach known as wracks (Bussotti et al., 2022). During the storm period, related surges facilitate the dislodging of submerged accumulations, propelling them towards the shore, where they remain in the water until the storm decreases (Balestri et al., 2011). The increasing anthropization of coastal zones, especially due to intensive tourism near submerged meadows, has led to the degradation and retreat of these seagrass habitats (Blanco-Murillo et al., 2022; Boudouresque et al., 2009). Several human activities contribute to this decline, including beach nourishment to enhance tourist beaches (Aragones et al., 2015), accumulation of UV filters from sunscreens (Agawin et al., 2022), nutrient-rich coastal discharges (Jimenez-Casero et al., 2023), vessel anchoring (Milazzo et al., 2004; Marba et al., 2002), and harbor expansion (De Luca et al., 2024). These stressors not only reduce the coverage of seagrass, but also promote the detachment of dead *Posidonia oceanica* material. Then, the gentler waves gradually transport all floating materials to the shoreline, forming structures known as banquettes (Trogu et al., 2023).

Posidonia oceanica banquettes continue to play an important ecological role on the beach (Boudouresque et al., 2025; Del Vecchio et al., 2017; Mateo et al., 2003), contributing to nutrient cycling through the release of carbon, nitrogen, and phosphorus derived from the decomposition of their leaves (Mateo et al., 2003). Furthermore, banquettes have been demonstrated to sustain intricate trophic networks by providing sustenance, shelter, and organic matter (Boudouresque et al., 2006). These accumulations, often seen as sedimentary formations, are the result of a gradual accumulation process involving sand, organic matter, and predominantly seagrasses. This is particularly evident in the landward regions where wave action is most pronounced (Simeone et al., 2013). The composition and grain size of the sand can exhibit notable variation from one beach to another, with sand constituting a significant portion of up to 70% of the total banquette mass (Astudillo et al., 2023). However, this percentage can fluctuate widely, ranging from 0.5% to 85%, influenced by factors such as the location of the banquette to the shoreline, hydrodynamics, sediment properties and beach characteristics (ISPRA, 2010). Even further inland, these accumulations can retain additional sediment through wind, contributing to the long-term stability of dune areas (Provost et al., 2022; Moller et al., 2021), although this action could affect the establishment of native plant species (Menicagli et al., 2025). Furthermore, the growth of seedlings stimulated by these accumulations helps facilitate the colonisation of new dune plants in bare sand areas (Menicagli et al., 2024).

The rapid urban expansion of the Mediterranean coastal regions between the 1930s and 1970s (Semeoshenkova and Newton, 2015), and the subsequent globalisation of coastal tourism from the early 21st century onwards (Cohen, 2012), has increased beach vulnerability (Villares et al., 2006). The removal of banquettes has been a common practice on most Mediterranean beaches, as a measure to preserve an aesthetic user demand, mainly from the tourism sector (Pikelj et al., 2022). Consequently, there has been a pronounced emergence of local economies focused on preserving coastal areas primarily for recreational purposes, often at the expense of the natural environment (Semeoshenkova and Newton, 2015). In this context, the recreational perspective of coastal management has predominated in beach cleaning, where local authorities prioritize the provision of an idealized rather than a natural environment (Simeone and De Falco, 2013). This perspective is largely influenced by the perception among tourists that the presence of seagrass accumulations along the shoreline represents a "dirty" element of the beach (Garcia and Servera, 2003).

Consequently, measures such as the implementation of the *Blue Flag* certification were adopted to promote tourism development and certify the environmental quality of beaches (Mir-Gual et al., 2015). Since its establishment in 1987 by the Foundation for Environmental Education in Europe (FEEE), the *Blue Flag* programme has been dedicated to improving beaches by applying strict criteria. The evaluation includes environmental education, water quality, environmental management, safety, and services (Nelson et al., 2000). Despite the wide scope of the programme, authors such as Merino and Prats (2020); Zielinski and Botero (2019); Lucrezi et al. (2015); Mir-Gual et al. (2015); McKenna et al. (2011), and Nelson et al. (2000) have criticized the *Blue Flag* programme on various coasts around the world, arguing that it focuses mainly on tourism services and does not give enough weight to the importance of environmental features. Criterion 16 of the *Blue Flag* (Flag, 2024) specifically states that "Algal vegetation or natural debris should be left on the beach" and should only be removed if its presence becomes a hazard, leaving the responsibility for cleaning the beach banquettes to the interpretation of the coastal administration.

Since 1995, to formalize protected areas of biodiversity interest, the Mediterranean region has collectively established regulatory frameworks under the Barcelona Convention (Rotini et al., 2020). Countries such as Italy, France, and Spain ratified this agreement, generating regulations aimed at protecting the accumulations. However, exemptions exist that confer municipalities the authority to determine the disposition of such accumulations (Boudouresque et al., 2017; Rotini et al., 2020).

Among these countries, Italy has taken a leading role in the legislation to manage *Posidonia oceanica* accumulations. It first introduced protective measures through National Circular 8838/2019, issued by the Italian Ministry of the Environment. This circular emphasises that the removal of accumulations endangers the integrity of coastal habitats, restricting the transit of heavy vehicles and extraction for compostable purposes (Rotini et al., 2020). Then, this document has been superseded by subsequent decrees and laws that establish specific conditions for managing *Posidonia oceanica* remains on beaches. Decree-Law No. 41/2021 (converted into Law No. 69/2021), in conjunction with Article 35(1)(b)(2-bis) of Decree-Law No. 77/2021 (converted into Law No. 108/2021), stipulates that *Posidonia oceanica* deposited on beaches is exempt from waste management regulations, on the condition that it is returned to the same marine environment or reused for agronomic purposes or as a substitute for raw materials in production cycles. These methods or processes must not cause harm to the environment or pose a risk to human health (Lolli, 2022). Finally, building on all previous legislation, Law No. 60/2022 (the Salvamare Law), enacted in May 2022, represents the first direct attempt to regulate the management of *Posidonia oceanica* accumulations and other plant biomass on beaches. Whilst this law represents a significant regulatory step forward within the European Union, it lacks a clear hierarchical framework for implementation (Amendola, 2022).

In Spain, the protection of *Posidonia oceanica* is enshrined in Law 42/2007, which prioritises the conservation of endangered habitats. The ecosystem is also listed among the wild species requiring special protection. It is included in the Spanish Catalogue of Threatened Species, as defined in Royal Decree 139/2011. These regulations generally prohibit the collection, transportation, sale or exchange of seagrass specimens, whether alive or dead. However, municipal authorities are responsible for overseeing these activities and may authorise the removal of accumulations from beaches under specific circumstances (Rotini et al., 2020). Regions such as the Balearic Islands enacted reinforced measures to protect *Posidonia oceanica* meadows through decree 25/2018 (Pergent-Martini et al., 2022). This legislation also prohibits the removal of accumulations from beaches, thereby bolstering natural conservation efforts on the shoreline. The situation in Catalonia is distinct, as there is no clear regional regulation requiring the protection of *Posidonia oceanica* accumulations on the beach. As a result, the management of these areas is delegated to individual local councils, within the parameters set by national regulations.

Given that the Catalan coast has been exposed to complex interactions between marine risks, such as storm-induced coastal floodings, and hydrometeorological risks, including flash floods (Romero-Martín et al., 2024). The retreat of beaches is a reality (CIIRC, 2010), and their recreational carrying capacity is expected to decrease over time, and the accelerated increase in sea level further exacerbates this situation (Lopez-Doriga et al., 2019). Additionally, anthropogenic pressures in the coastal zone have exerted stress on seagrass habitat. This is evidenced by a reduction in seagrass meadow density and a retreat in depth (Pansini et al., 2021; de Dios et al., 2012), thereby affecting the frequency of occurrence of banquette-type structures on the shoreline. In this scenario, implementing effective tourism policies that preserve nature is a significant challenge. This is particularly important as tourism contributes significantly to the economy of the Catalan coast, representing approximately 11% of the gross domestic product of the region (Garola et al., 2022).

In this regard, it is imperative to evaluate the effectiveness of measures that can help mitigate the ongoing changes affecting coastal regions. *Posidonia oceanica* accumulations offer a nature-based alternative for protecting shorelines from erosion (Astudillo-Gutierrez, 2024). While data on their distribution and impact remains limited, it is essential to assess their physical properties to support their role as a coastal protection strategy. To address this knowledge gap, the present study focuses on identifying the areas where banquettes occur along the Catalan coast, examine how they are managed, and characterize the physical properties of nascent banquettes that contribute to erosion protection, as outlined in the process diagram presented in Figure 1.

In light of the dearth of research on banquettes in this region, surveys were conducted throughout more than 100 kilometres of coastline to document their presence on coastal beaches. Furthermore, local beach managers were contacted to gather further information on beach cleaning practices. The physical parameters of the banquettes were evaluated using nascent formations observed on Pixavaques Beach as a reference. Three types of assessment were conducted on these shoreline accumulations: permeability tests, quantification of sediment retention, and penetration resistance measures. The first two tests were performed in the laboratory using undisturbed samples and aimed to characterise key parameters relevant to the role in mitigating erosion. In contrast, the penetration resistance test was conducted on site and may reflect the degree to which these structures are anchored in the sand, based on their relationship with sediment content.

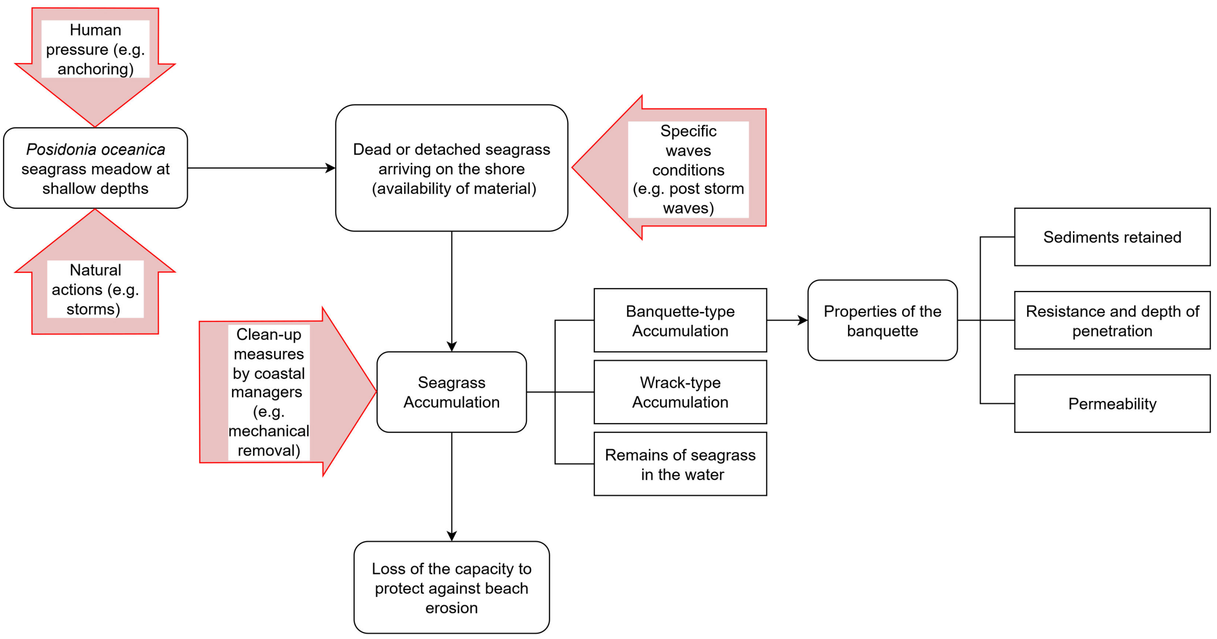

FIGURE 1
Conceptual diagram illustrating the key factors addressed in this study, including processes, management actions, and physical properties of *Posidonia oceanica* banquettes relevant to coastal protection.

2 Study area

The study of the *Posidonia oceanica* accumulation was focused on the southern coast of Catalonia (Spain), covering 110 km between the municipalities of Calafell and Deltebre (Figure 2A). The landscape of this area is predominantly composed of low-lying beaches of fine sand. The coasts are characterized by a micro-tidal range, and a wide shelf, with a quasi-permanent slope current (Bolaños et al., 2009). The astronomical tidal range is less than 0.4 m, but during storms, the associated surge can increase water levels by up to 1 m (Sanchez-Arcilla et al., 2016). The monthly-averaged significant wave heights in southern Catalonia, as derived from *Puertos del Estado* buoy data in Tarragona (1992–2025), range from 0.23 m to 1.42 m, with the majority of values falling within the 0.4–0.8 m interval. The maximum significant wave height recorded during this period was 7.41 metres, observed during the Gloria storm in January 2020. Predominant winds come from the NW and the N during December and January. Southerly and easterly winds are also important during February, March, April and November (Bolaños et al., 2009). The directional distribution of waves along the southern Catalan coast shows a predominance of NW and N wave conditions at the southern and northern sections of the coast (Sierra et al., 2015).

The southern part of the Catalan coast includes 16 municipalities, which belong to four different counties. This represents over 25% of the total number of municipalities on the Catalan coast. The local economy is based on various activities, including commerce, agriculture, housing, and tourism. In particular, the tourism industry represents the most significant economic sector in southern Catalonia (Duro and Rodríguez, 2011). The study area exhibits a greater presence of *Posidonia oceanica* meadows compared to the other surrounding areas. This is in contrast to the area of the Ebro Delta area, where the *Cymodocea Nodosa* dominates as submerged meadow (Ruiz et al., 2015). The formation of seagrass banquettes depends on the availability of detached plant material. This means that coastal areas with seagrass meadows are more likely to experience banquette accumulation than areas without this vegetation (Boudouresque and Thommeret, 1981; Jeudy de Grissac, 1984; Holon et al., 2015).

2.1 Selected beach for banquette physical analysis

The municipality of L'Ametlla de Mar has 22 inlets and beaches spread along 20 km of coastline. In the northern area, the beaches present fine white sand, while in the southern area, there are more isolated rocky beaches with large areas protected due to their high ecological interest. Most of the beaches (81.8%) are composed of sand, with a D_{50} value ranging from 0.174 to 1.84 mm. The remaining 18.2% represents gravel beaches (CIIRC, 2010). The mean significant wave height (H_s) recorded is 0.81 m and the mean peak period (T_p) is 5.24 s (CIIRC, 2010). The Pixavaques Beach (Figure 2B) is located in this municipality, at 40°53' 12.722" N 0°48' 25.086" E. The beach is oriented in a north-easterly direction and measures 61 metres in length and 22 metres in mean width. This beach is bordered by two rocky outcrops at both ends, providing natural shelter. The sediment D_{50} value is 0.175 mm, with an average slope of between 0.04 and 0.07 mm and a mean run-up of between 0.19 and 0.26 m. This latter value is one of the lowest in southern Catalonia (CIIRC, 2010).

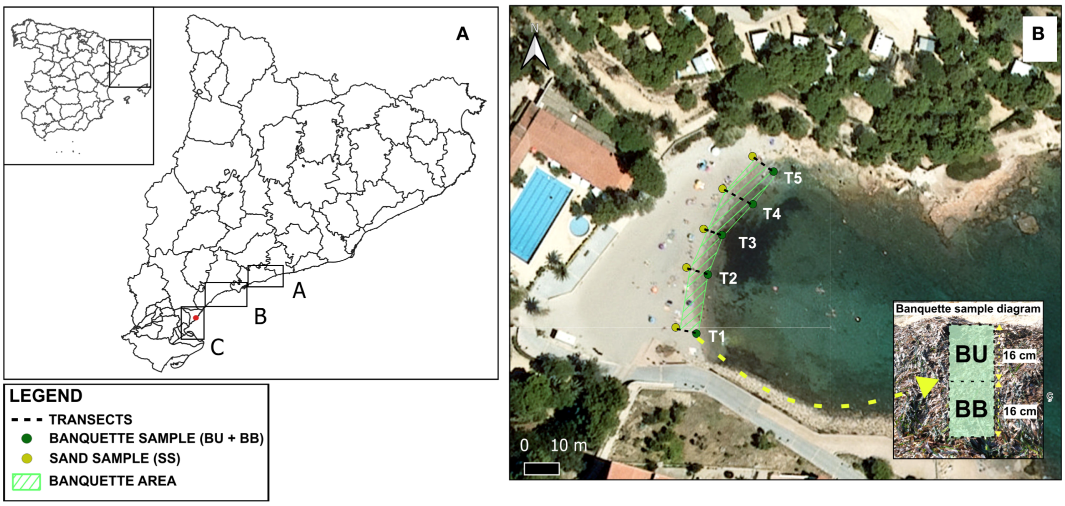

FIGURE 2
(A) Map showing Catalonia and its district limits. Black rectangles represent the three zones selected to exemplify the accumulation (detailed in Figure 4). The red circle in the C zone represents Pixavaques Beach. **(B)** The map shows the study area, where the transects are represented as a black dotted line and the sample sites as green (banquette) and yellow (sand) dots. The green dashed area indicates the extent of the banquette coverage. A sample diagram of the banquettes is displayed in the lower right box. BU represents upper banquette and BB represents bottom banquette.

Pixavaques Beach experiences recurrent banquette-type accumulations of *Posidonia oceanica*. Due to the wide range of services it offers and its convenient location, it is a popular destination for both tourists and visitors. To maintain its appeal as a tourist destination, the municipality regularly removes the banquettes in advance of peak tourism periods. However, new accumulations consistently form during autumn and winter. This ongoing cycle of removal and natural deposition offers an ideal opportunity to study the ecological and management implications of these events. The repeated formation of new banquettes allows for the evaluation of their early-stage characteristics and provides insights into the interaction between natural coastal dynamics and human interventions. It is imperative that such understanding is in place to facilitate informed decisions regarding conservation and sustainable beach management.

3 Materials and methods

3.1 Beach accumulation observation and interview with the beach-cleaning municipalities staff

In March 2022 and January 2023, two field surveys were conducted on the beaches located in the study area to document occurrences of banquette accumulations. Observations were classified according to the type of accumulation (Figure 3) in Banquette Type (BT), Wrack Type (WT), and No Accumulation (NA). When the accumulations were structured continuously and with a height of 10 cm or more, they were classified as BT. If the accumulations were unstructured, discontinuous or with isolated remnants of *Posidonia oceanica*, they were classified as WT. The beaches without any type of remains were designated as NA. During the first field campaign, an interview was conducted with the local municipality staff responsible for beach cleaning (Table 1). This interview was conducted following a semi-structured conversation (Horton et al., 2004). In cases where this was not possible, a questionnaire was utilized to gather relevant information about *Posidonia oceanica* seagrass accumulation (see Table 1). In both cases, the aim was to find the frequency with which banquette accumulations occurred over time, to identify beaches where mechanical cleaning was carried out, and the methodology employed for the disposal of the *Posidonia oceanica* remains. As part of this survey, Pixavaques Beach was selected from this region to analyse the physical characteristics of the banquette and the impacts produced on the beach due to the mechanical cleaning of the banquette, as detailed in the next subsection.

3.2 Data and sample collection

Pixavaques Beach was subdivided into five transects, each aligned perpendicular to the shoreline, as shown in Figure 2B. For each transect, the length and height of the banquette were measured and are presented in Table 2. In the proximity of the shoreline for each transect, two sets of banquette samples were collected. The first one was selected from the upper part of the banquettes (BU), while the other one was collected from the immediate lower part of the BU sample (BB). Each sample was deposited into a cylindrical plastic container 16 centimetres high, matching the height of each

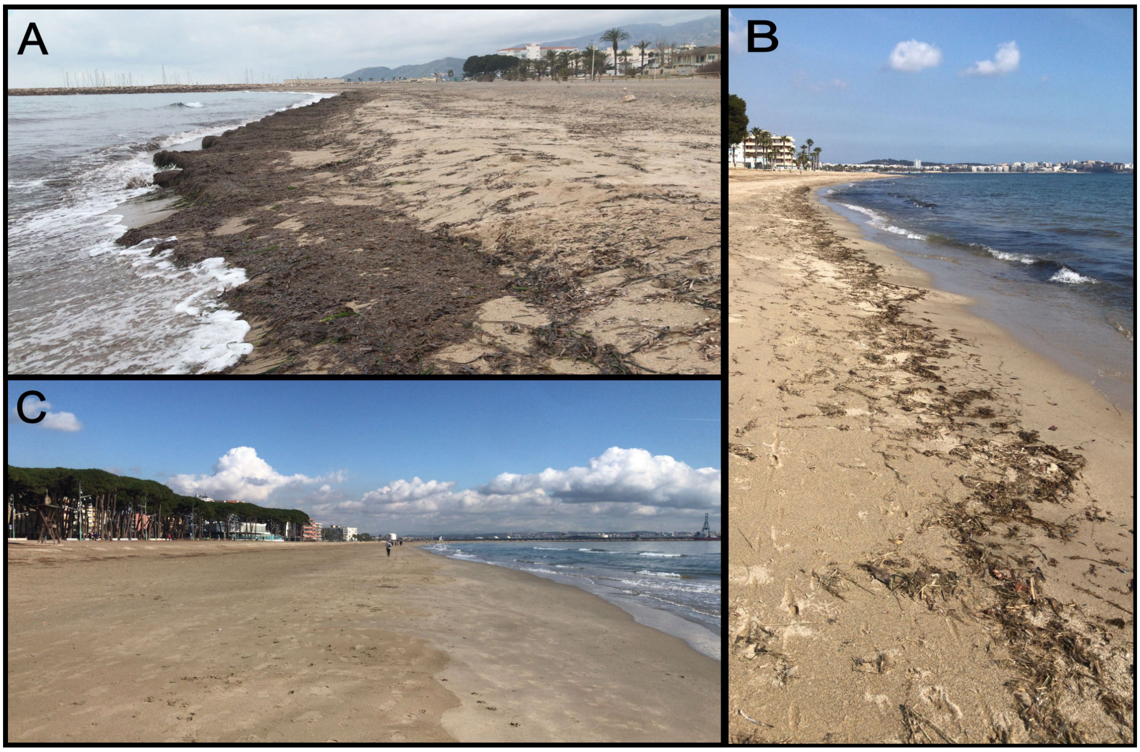

FIGURE 3
Examples of the type of accumulation. **(A)** Banquette-type Accumulation (BT) at Punta Riu Beach. **(B)** Wrack-type Accumulation (WT) at Cap de Sant Pere Beach. **(C)** No Accumulation (NA) at Pineda Beach.

TABLE 1 Questionnaire used for interviews regarding *Posidonia oceanica* banquette management.

Item	Question
1	When did the cleaning of *Posidonia oceanica* start? Is there a registration of the *Posidonia oceanica* cleaning completed?
2	Which type of machinery is used (brand/model)? How is the cleaning done?
3	Has the machinery always been the same? If there were any changes, since when? Why was the machinery changed?
4	Who cleans the beaches that present *Posidonia oceanica*: external company or city hall officers?
5	What is the cleaning frequency? When do you consider peak and low seasons?
6	What is your consideration on low frequency (once a week, once a month…)?
7	What is your consideration on low and high *Posidonia oceanica* accumulation? How is it determined? Is it determined in percentages?
8	During peak season, what do you do with *Posidonia oceanica* remains that are removed from the beach?
9	Are there any standards or regulations that apply to the cleaning of *Posidonia oceanica* from the beach?
10	Is there a beach nourishment?
11	How much is the beach cleanup budgeted at?

sample, and a volume of 2.1 l. Subsequently, these containers were transported to the laboratory for thorough analysis. Additionally, for each transect, a sand sample (SS) was collected from the upper part of the beach, located at the nearest point to the banquette, where there were no *Posidonia oceanica* remains. A total of five BU, five BB and five sand samples were collected.

3.3 Resistance to Penetration

To determine the penetration resistance (*P*), a perpendicular force was applied to a metal rod with a conical tip using an Eijkelkamp hand-held penetrometer. This instrument is capable of measuring up to a maximum depth of 100 cm. The rod was pushed through the sand and banquette surface, and in each instance of force application, the depth of penetration and the maximum magnitude of the force indicated by the manometer of the equipment were recorded. The *P* measurements were conducted at Pixavaques Beach. To compare the variability in the profiles, three *P* measurements were taken in the vicinity of both sand and banquette samples of each transect. In all tests performed in this experiment, the metal rod with a conical tip was utilized, with a basal area of 5 cm^2. The penetration resistance was calculated by dividing the manometer reading by the area of the cone base for each depth.

TABLE 2 Dimensions of the banquette for each transect.

Transect	Length (m)	Height (m)
T1	5.3	0.30
T2	4.8	0.70
T3	5.7	0.65
T4	7.4	0.84
T5	7.0	0.55

3.4 Laboratory and data analysis

3.4.1 Sediment retention

Granulometric analysis was conducted on all samples (five from bare sand and ten from the banquette). The samples were oven-dried at 80 °C for 48 hours. Particle separation was carried out using eight sieves with mesh sizes ranging from 2.0 to 0.063 mm. A sieving time of 10 minutes was applied, following the recommendations of Roman-Sierra et al. (2013). For banquette samples, the methodology described in Astudillo et al. (2023) was used. The 2.0 mm sieve was used to separate the coarser *Posidonia oceanica* remains, and excluded from the organic matter removal procedure. This was based on the assumption that the sand retained in this sieve constituted less than 5% of the total material analyzed and did not interfere with the final results of the sediment distribution. To eliminate the organic matter (OM), a subsample of the sieves from 1.0 to 0.063 mm underwent a thermal oxidation process. The material from each subsample was calcined at 500 °C for 30 minutes inside a muffle furnace to facilitate the OM removal, allowing for the determination of the weight of the retained sediment (muffled weight). The OM percentage of each sieve ($OM_{(s)}$) was calculated according to Equation 1, and the weight of sediment retained by the banquettes on each sieve ($WC_{(s)}$) was obtained from Equation 2.

$$OM_{(s)} = \frac{(W_{sd} - W_m)}{W_{sd}} x100\,\% \qquad (1)$$

$$WC_{(s)} = W_d x(1 - OM_{(s)}) \qquad (2)$$

W_{sd}represents the dry weight of the subsample for each sieve, and $W_m$is the muffled weight of the same sieve after the thermal oxidation process. To obtain the value of $WC_{(s)}$, the dry weight of each sieve $W_d$was adjusted by subtracting the proportional percentage of $OM_{(s)}$ as defined in Equation 2). Statistical values of sediment sieve samples, such as D_{50}, sorting (Sr), and skewness (Sk) were analysed by employing the computational tool SANDY, specifically developed for Matlab software (Ruiz-Martínez et al., 2016). The sediment retained in each banquette sample was calculated by adding the values of $WC_{(s)}$ for each sieve. These totals were then divided by the sample volume (V_{sample} = 2.1 l) to obtain the representative value of sediment retention per cubic meter of banquette (Equation 3).

$$Sediment\ \ retained = \frac{\sum_{i=1}^{s} WC_{(s)}}{V_{\text{sample}}} \qquad (3)$$

3.4.2 Permeability

The permeability tests were conducted at the Geotechnical Laboratory of the University Polytechnic of Catalonia - BarcelonaTech (UPC). Both sand (1) and banquette (2) samples were subjected to a hydraulic conductivity test using a constant charge permeameter, following the methodology employed in the sand permeability experiments outlined in Spagnoli et al. (2022). The permeability of the banquette was evaluated using samples extracted from two distinct locations on the beach. The first sample was obtained from the banquette at the shoreline, and the second from a banquette located 1.5 meters inland from the shoreline. A third sample involved measuring the permeability of the initial shoreline banquette sample after it had been manually compacted inside a vessel. To facilitate the comparison of permeability values, a sample of bare sand from the beach was also examined.

The samples were contained within the cylindrical permeameter vessel of area A. A constant flow rate of water (Q) was applied, passing through the sample. The volume of water variation (ΔV) traversing the sample in a time interval (Δt) was measured, enabling the determination of Q. Two vertically spaced tubes, positioned at a distance of 15 cm (d), each equipped with piezometers, enabled the measurement of water columns in each tube ($h_a$and h_b). Using Equation 4, the permeability value (k) was derived. Four measurements of k were recorded for each sample, and an average of these values was calculated for analysis.

$$Q = \frac{\Delta V}{\Delta t} = k{*}A{*}\frac{h_a - h_b}{d} \qquad (4)$$

4 Results

4.1 Classification and management of the *Posidonia oceanica* accumulation along the southern Catalan coast

Figure 4 illustrates the map of the presence of banquette (BT) and wrack (WT) accumulation observed in this study. 85 beaches were surveyed, of which 35.3% were found to have significant BT accumulation. Furthermore, 36.5% of the total beaches displayed WT accumulations, and 28.2% had no accumulated seagrass remains. From Calafell to Tarragona (Figure 4A) did not exhibit BT accumulations, and less than 50% of the beaches in this area had a WT accumulation. From Salou to the South of Catalonia (Figures 4B, C) the BT accumulation was more pronounced. In this area, banquettes were predominantly observed in sheltered areas of the beaches, near the breakwater, in front of seawalls, or in naturally protected areas. Other BT accumulations were found in pocket beaches, where the accumulations covered the entire shoreline. The most exposed areas of the beach did not present accumulations.

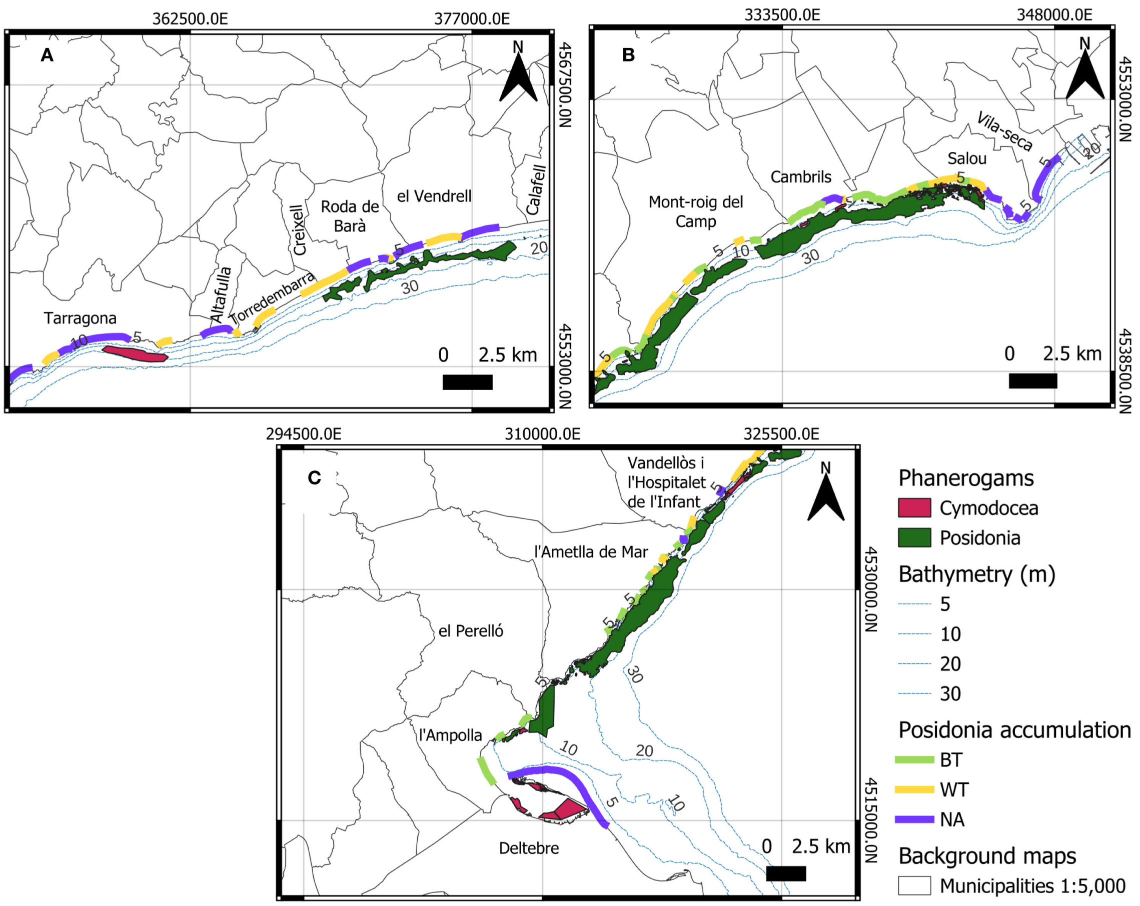

FIGURE 4
Accumulation of *Posidonia oceanica* and *Cymodocea nodosa* along the southern coast of Catalonia, segmented into three sections labeled **(A)** Calafell to Tarragona, **(B)** Vila-seca to Mont roig del Camp, and **(C)** Vendellòs i l'Hospitalet de l'Infant. BT stands for Banquette Type, WT stands for Wrack Type, and NA stands for No Accumulation.

Out of the 16 municipalities surveyed (Figure 4), nine (three interviews and six via questionnaire) were available to answer the questions about the management of *Posidonia oceanica* accumulations. Every municipality consulted reported occurrences of accumulations on their beaches at various times over the last 10 years. Eight of the nine (88.9%) municipalities surveyed reported removing *Posidonia oceanica* accumulations that appeared on the beach. The exception was the municipality of Altafulla, where accumulations are isolated and do not generate large volumes or banquette structures. The accumulations removed are transported to collection points situated outside the beach area. For cleaning operations, all municipalities have utilized heavy machinery, particularly excavators (Figure 5A). However, only four of them (Vandellos i l'Hospitalet de l'Infant, Roda de Bara, L'Ametlla de Mar, and Deltebre) have upgraded their machinery in recent years, incorporating screening machines (Figure 5B) to minimize sand removal during the process. Nevertheless, there were pocket beaches which, due to their small size for manoeuvring and access difficulties, were unable to employ screening machines. In such cases, the only viable option was the use of heavy machinery to remove the banquettes.

In all municipalities, the cleaning season is focused on the period before summer and extended weekends, such as Easter week, which is a peak season characterized by increased tourist activity (Torres Sole et al., 2015). Due to the lack of records, it was not possible to obtain an estimate of the total volume of banquettes removed at each location and period. Furthermore, each municipality funds the costs of this work from the annual beach cleaning budget. There is no specific allocation for banquette removal, which makes it impossible to obtain an annual estimate of removals.

The cleaning in Pixavaques Beach is conducted by five municipal operators, using a mixing machine and trucks. The operators are aware of the importance and conservation of the dune systems and the monitoring of the nesting of species such as the Mediterranean loggerhead sea turtle (*Caretta caretta*). During peak season, beach cleaning operations are conducted daily. Until 2015, this process involved the use of a tractor shovel with a plough to aerate the sand. However, the procedure was changed due to significant sand removal caused by the excessive penetration of the shovel into the sand. Subsequently, an upgrade was implemented, utilizing a screening machine (Barber Surf brand) towed by a 120

FIGURE 5
(A) Cleaning Cala de l'Estany Tort (L'Ametlla de Mar) with an excavator. **(B)** Cleaning of Punta del riu Beach (Vandellos and l'Hospitalet de l'Infant) with a tractor and a coupled screening machine.

CV truck of the New Holland brand. Once the *Posidonia oceanica* was collected, it was transferred to a John Deere cart. The accumulated material is deposited in a designated municipal property, where it has been stored since the early 1990s. In the low season, beach cleaning activities are suspended entirely, allowing for the natural deposition of *Posidonia oceanica*.

4.2 Sediment retention

Applying the thermal oxidation process for each of the banquette samples and employing Equation 1, the OM removal values of *Posidonia oceanica* remain for every sieve, averaged across the five transects, are detailed in Table 3. Notably, the organic matter removed decreased with diminishing sieve size, except in the smallest sieve (0.063 mm), which exhibited a substantial presence of OM. Subtracting the *Posidonia oceanica* remains from each sieve allowed the determination of the sediment retained by each banquette sample (Equation 2).

Table 4 shows the amount of sediment retained by each banquette after subtracting the OM values using Equation 3. The highest sediment retention was observed at T4, both at the top (BU) and the bottom (BB) of the banquette, reaching between 10 and 30 kg per m^3, respectively. T3 (28 kg per m^3) and T5 (5 kg per m^3) also had higher sediment retention at BU and BB, respectively. T1 had the lowest sediment retention of all the transects, reaching less than 2.4 kg per m^3.

The mean and standard deviation (*STD*) of sediment passing in each sieve from the five transects are detailed in Table 5. The banquette samples were analysed without the 2 mm sieve, resulting in 100% of sediment passing through it. In contrast, the sand samples passed through the same sieve with a rate exceeding 98%, indicating minimal retention in the 2 mm sieve. This high passing rate did not introduce significant alterations in the granulometric analysis when comparing it with the sediment retained in the banquette. Table 5 reveals that the 0.350 mm and 0.250 mm sieves exhibited the highest variability percentage of the banquette samples. Conversely, the 0.125 mm and 0.063 mm sieves displayed the lowest *STD* (%) variability, indicating more consistent results on the fine sand range.

Figure 6 compares the mean sediment retained in different sieve sizes along the five transects. As illustrated, sediment retention was predominantly concentrated in the 0.25 mm, and 0.125 mm sieves.

TABLE 3 Mean and standard deviation from five transects of the percentage of organic matter (OM) removed from each sieve for the BB and BU banquette samples.

Sieve (mm)	BB		BU	
	Mean (%)	SD (%)	Mean (%)	SD (%)
2.000	–	–	–	–
1.000	54.90	6.93	57.98	8.54
0.710	52.01	11.21	55.99	10.84
0.500	47.27	16.10	48.73	14.85
0.355	38.66	18.03	30.89	15.89
0.250	27.02	20.47	14.98	12.75
0.125	14.99	15.53	10.22	11.80
0.063	34.00	17.93	31.83	22.93

TABLE 4 Sediment retained and estimated weight per 1 m^3 of banquette in both BU and BB samples across each transect.

Sample	Sediment retained (kg)	Estimated sediment (kg/m^3)
T1-BB	3.613×10^{-3}	1.72
T1-BU	5.022×10^{-3}	2.39
T2-BB	9.078×10^{-3}	4.32
T2-BU	9.153×10^{-3}	4.36
T3-BB	4.276×10^{-3}	2.04
T3-BU	5.897×10^{-2}	28.08
T4-BB	6.336×10^{-2}	30.17
T4-BU	2.139×10^{-2}	10.19
T5-BB	1.109×10^{-2}	5.28
T5-BU	6.703×10^{-3}	3.19
Mean	1.927×10^{-2}	9.17

This last sieve retained an average of 44.68% of sediment in the sand samples, 52.20% in the upper banquette and 42.60% in the bottom banquette. In contrast, the lowest sediment retention occurred on the 0.063 mm sieve, with no variability between the three types of samples. The sieves above 0.250 mm exhibited low values of sediment retention, with similar magnitudes between them. According to the classification by Wentworth (1922), the sediment retained across all samples was identified as fine sand.

The sediment retained in the banquettes was finer than that of the bare sand. Figure 7 illustrates the mean granulometric curve for each type of sample. The BB sample exhibited slightly finer sediment retention than the sand sample, while BU demonstrated even finer retention. This supports the findings of the *Sk* values above 0.3 in the BU and BB samples, which were also higher than those of SS.

TABLE 5 Mean and standard deviation of sediments passing through each sieve for the three sample types (SS, BB, BU) across five transects.

Sieve (mm)	SS		BB		BU	
	Mean (%)	STD (%)	Mean (%)	STD (%)	Mean (%)	STD (%)
2.000	98.20	1.05	100.00	0.00	100.00	0.00
1.000	96.09	2.11	85.85	7.38	91.47	7.96
0.710	93.87	2.74	80.27	10.44	87.55	10.69
0.500	87.02	4.32	73.65	14.47	83.14	12.88
0.355	73.58	5.22	65.92	16.74	75.80	15.23
0.250	47.44	3.96	50.18	13.67	54.72	16.34
0.125	2.80	0.71	3.80	1.73	2.74	0.68
0.063	0.32	0.20	0.47	0.63	0.11	0.11

The statistical values of the sediment retained in samples, including D_{50}, skewness (*Sk*) and sorting (*Sr*) are presented in Table 6. The D_{50} sand sample values exhibit low variability, averaging 0.259 mm across the five transects. In contrast, the sediment retained in the banquette samples shows high variability. Depending on the transect evaluated, the sediment was either coarser (T1 and T2) or finer (T3, T4, and T5) than the D_{50} of the sand collected from the corresponding transect. A comparison of the sediments retained at BB with those retained at BU revealed that, except for T2, the sediments retained at BB were of a similar or coarser size to those retained at BU. The *Sr* values in the SS samples ranged from 0.88 (T4) to 0.90 (T2 and T3). In contrast, the values in the BB and BU samples exhibited greater variability. For BB, the *Sr* values ranged from 0.81 (T4) to 1.04 (T3 and T5), while in BU, the values ranged from 0.80 (T3) to 1.04 (T1). The mean values of *Sr* for the three types of samples were found to be moderately sorted. The *Sk* values in the banquette samples vary between -0.23 to 0.59, and they were higher than the bare sand, except for transect T1. The mean values of *Sk* of both BU and BB were higher than 0.3, and according to the classification, the banquette samples were very fine-skewed, while the sand samples were fine-skewed.

4.3 Permeability

Permeability values (*k*) for all tested samples are detailed in Table 7. The mean permeability recorded for the sand samples from Pixavaques Beach was 0.051 cms^{-1}. The nascent banquette, located at the shoreline position, had the highest permeability of all samples, with an average value of 16.41 cms^{-1}. The banquette samples, extracted from a distance of 1.5 m from the shoreline, presented a mean permeability value of 0.324 cms^{-1}, considering three of the four tests carried out. When compacting the banquette sample located at the shoreline, the permeability decreases to a mean of 0.191 cms^{-1}, which was lower than the permeability of the natural banquette but still higher than the permeability of the sand.

4.4 Resistance to penetration

In the evaluation of Pixavaques Beach, the penetration resistance measured in each transect is presented in Figure 8. In the sand area (Figures 8A, C, E, G, I), the resistance values presented an upward trend with increasing depth, ranging from 0.42 MPa at a depth of 5 cm to 1.84 MPa at 20 cm. In contrast, the banquette (Figures 8B, D, F, H, J) exhibited high variability in resistance values between measurements obtained in the same transect. There was no clear pattern of resistance with the height of the banquette. However, in most tests conducted, the resistance in the first 20 cm did not exceed 1.0 MPa, with two exceptions: transect T3 and transect T5. In the transect T3 (Figure 8f), one of the measurements reached a resistance of 1.62 MPa at 10 cm of depth, while in transect T5 (Figure 8J), another measurement recorded a resistance of 1.34 MPa at a depth of 5 cm. In the other banquette transects, the

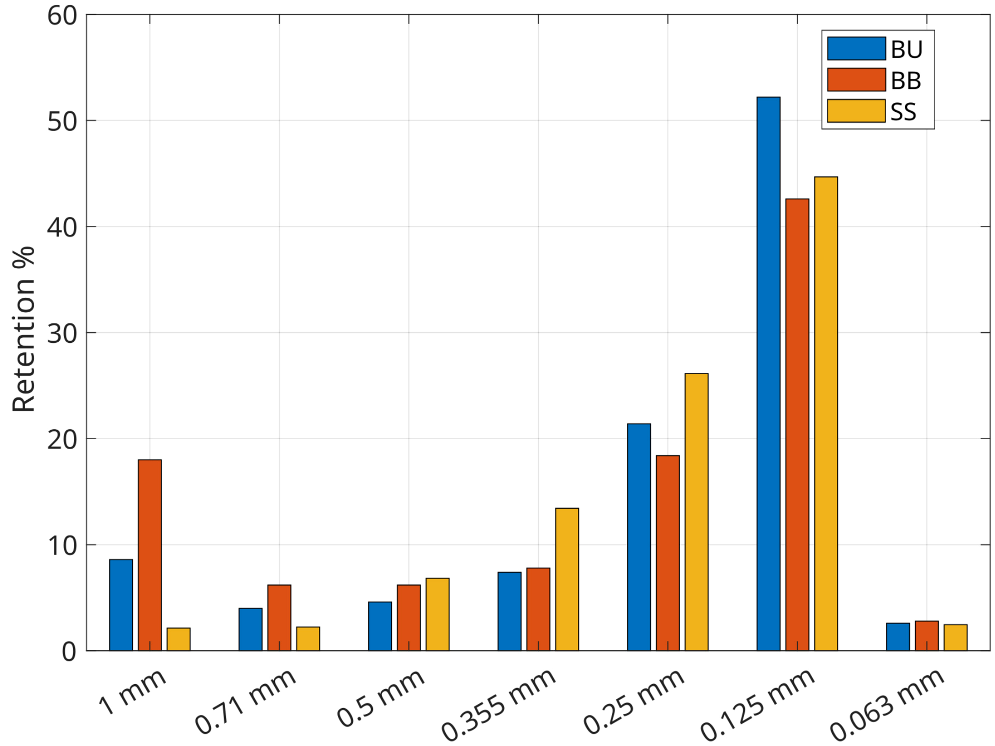

FIGURE 6
Mean sediment retained per sieve across five transects for SS, BU, and BB samples.

maximum values obtained were typically observed at depths greater than 20 cm. Notably, only in transect T3 there were peak resistance values similar to those observed in the sand transects at a depth of 20 cm. At the maximum depth of the banquette samples collected for this study, delimited by a red dotted line in Figures 8B, D, F, H, J, transects T1 and T4 exhibited resistances of penetration below 1.0 MPa. In contrast, transect T2, T3, and T5 displayed resistances exceeding 1.0 MP, albeit with an abrupt decrease between 15 and 20

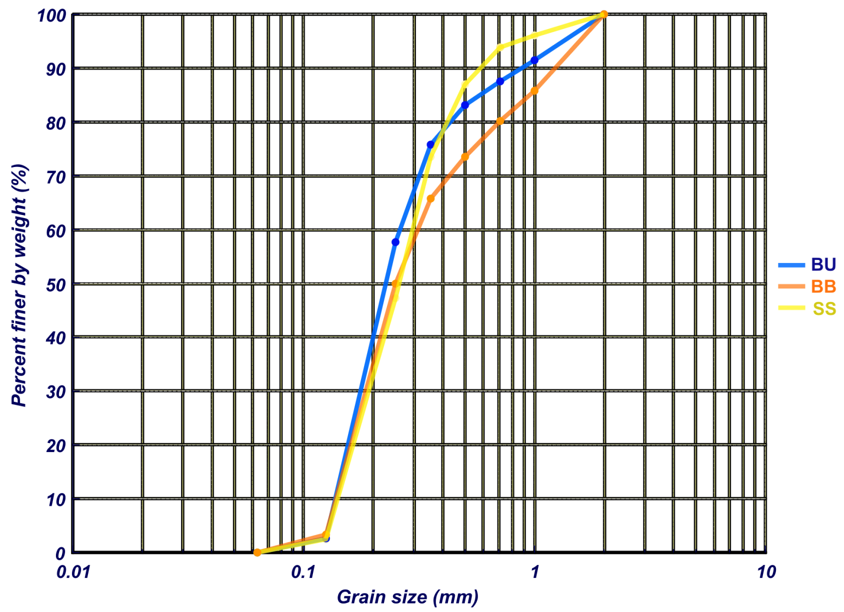

FIGURE 7
Granulometric distribution of the average of five sediment samples for SS, BU, and BB.

TABLE 6 Median particle diameter (D_{50}), sorting (Sr), and skewness (Sk) for each sample and transect.

Transect	D_{50} (mm)			Sorting (Sr)			Skewness (Sk)		
	SS	BU	BB	SS	BU	BB	SS	BU	BB
T1	0.25	0.33	0.47	0.89	1.04	1.03	0.28	0.26	-0.23
T2	0.25	0.28	0.26	0.90	0.96	0.98	0.13	0.32	0.45
T3	0.28	0.22	0.27	0.90	0.80	1.04	0.21	0.39	0.38
T4	0.25	0.22	0.22	0.88	0.81	0.81	0.27	0.43	0.36
T5	0.25	0.21	0.22	0.89	0.87	1.04	0.27	0.23	0.59
Mean	0.26	0.25	0.29	0.89	0.98	0.98	0.23	0.33	0.31

cm below. Note that in transects T2 and T5, maximum values were subsequently observed in the deeper section of the banquette after the reduction in resistance.

5 Discussion

Banquette-type accumulations occur when a confluence of factors are aligned: an abundance of available materials and specific wave and wind conditions conducive to their transportation to the shoreline (Fernandez-Mora et al., 2025; Trogu et al., 2023). The banquettes composed of *Posidonia oceanica* originate from adjacent submerged meadows, uprooted by wave action and subsequently deposited on the beach as accumulations. In addition, these formations can arise from plant debris from the sea or from the decomposition of previous banquettes (Trogu et al., 2023).

Conversely, the dismantling of these accumulations occurs under different wave and wind conditions than those that led to their formation. Well-defined and wrack-type accumulations can be dismantled by low-energy waves, particularly by spilling-type breakers (Fernandez-Mora et al., 2025), often just before the occurrence of a storm (Trogu et al., 2023; Gomez-Pujol et al., 2013). In other cases, portions of the banquette may migrate inland toward dune zones due to wind action (Jimenez et al., 2017), and some of this biomass may not return, remaining instead deposited in submerged coastal areas (di Montanara et al., 2024).

According to the *Atlas de las praderas marinas de España* (Ruiz et al., 2015), the dominant seagrass meadows between Calafell and Tarragona are composed of *Posidonia oceanica* and *Cymodocea nodosa*, with *Posidonia oceanica* typically found at depths more than 5 m (see Figure 4A). The absence of meadows, or their occurrence farther offshore, suggests a limited supply of plant material necessary for banquette formation. The availability of *Posidonia oceanica* plants is essential, and these can be transported from submerged meadows or when floating parts of the plants are available along the surf zone (Trogu et al., 2023). This pattern is consistent with the observed decrease in banquette-type accumulations along this section of coastline (see Figure 4A). For instance, the municipality of Altafulla has not experienced *Posidonia oceanica* banquette-type accumulations on its beaches for over a decade, except *Cymodocea nodosa* deposits following storm Gloria in January 2020.

From the municipality of Salou southwards, *Posidonia oceanica* meadows are found at depths less than 5 m. Nevertheless, the greatest extent of coverage occurs within the depth range of 10 to 20 m (Ruiz et al., 2015). The presence of seagrass meadows in shallower regions has been found to relate with a higher probability of the occurrence of banquette-type accumulations at the shoreline, consistent with the findings of this study (Figures 4B, C). The largest *Posidonia oceanica* banquette occurred on sheltered beaches. This observation aligns with previous studies by Zielinski et al. (2019) and De Falco et al. (2008), who reported that accumulation and persistence of banquettes were greater on beaches characterized by lower wave energy and favourable weather conditions.

The spatial relationship between the depth of the seagrass meadows and the occurrence of banquette accumulations is influenced by the prevailing wave conditions in this sector of the Mediterranean. In areas of higher wave energy, the active hydrodynamic layer extends deeper into the water column, enabling the detachment and transport of *Posidonia oceanica* fragments from greater depths towards the shore, where they accumulate (Marco-Mendez et al., 2024; Trogu et al., 2020; Gera et al., 2014). Furthermore, the impact of human activities, including chemical discharges (Jimenez-Casero et al., 2023; Apostolaki et al., 2010), rising sea temperatures (Marba and Duarte, 2010), changes in the sediments balance (Bonamano et al., 2021; Ruju et al., 2018), biological invasions (Deudero et al., 2011; Peirano et al., 2005), and vessel anchoring (Zenone et al., 2025; Montefalcone et al., 2006), can contribute to the degradation of seagrass meadows, resulting in the dislodgement of shoots and rhizomes. Once detached, seagrass

TABLE 7 Permeability values (k) for different samples.

Test	Sand	Banquette (shoreline position)	Banquette (1.5 m from shoreline)	Compacted banquette
$k1$	0.030	0.78	0.234	0.116
$k2$	0.045	7.70	0.324	0.169
$k3$	0.058	19.45	0.414	0.228
$k4$	0.070	37.73	—	0.248
Mean k	0.051	16.41	0.324	0.191

Values expressed in cm s^{-1}.

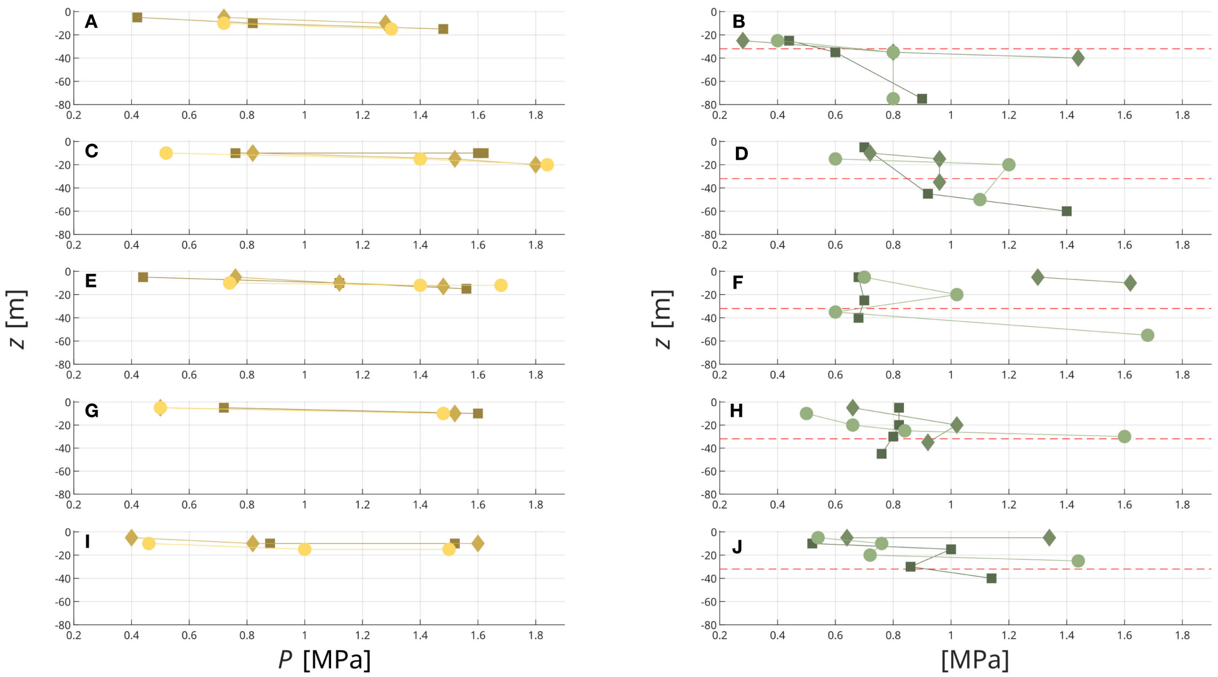

FIGURE 8
Resistance to penetration for Sand/Banquette across the transects T1 **(A, B)**, T2 **(C, D)**, T3 **(E, F)**, T4 **(G, H)** and T5 **(I, J)**. Rectangles, diamonds, and circles represent the three different measurements made on the same transect. The yellow shades represent measurements taken in the sand area, while the green shades correspond to measurements conducted in the banquette area. The red dotted line indicates the final position of the bottom banquette cylindrical sample (32 cm of depth).

remains become available for coastal accumulation, playing a critical role in banquette formation.

Understanding this process is essential, as future scenarios, including sea level rise, increasing water temperatures, and other environmental stressors (Guerrero-Meseguer et al., 2017), are expected to drive the retreat of seagrass meadows. Such a decline would reduce the supply of organic material necessary for the accumulation of coastal banquettes, thereby undermining the formation and persistence of these protective structures within the framework of existing conservation strategies in this Mediterranean region. These potential impacts remain inadequately addressed and should be prioritized in future research, particularly given that coastal erosion is a critical issue affecting the Mediterranean beaches (Romero-Martín et al., 2025).

Based on interviews with the local municipality staff, beaches in the study area have undergone the removal of *Posidonia oceanica* accumulations since the late 1980s - early 1990s. In 1992, the first *Blue Flag* cleaning initiatives were introduced on Calafato beach (municipality of L'Ametlla de Mar). Since then, the practice of removing these accumulations has continued throughout the entire study area up to the present day. However, mitigation measures to reduce the impact of these removals have been adopted, consisting of three main strategies: 1) All consulted municipalities have reported that banquette removals have been limited to peak periods over the last decade. During periods of low tourist influx, accumulations are left undisturbed on the beach. 2) Fifty percent of the consulted municipalities have upgraded their machinery to minimize sand removal from the beaches. 3) Only two out of the nine consulted municipalities have indicated that they intend to relocate accumulations to the back of the beach.

Considering the significant degree of erosion on the beaches of the Catalan coast (Sanchez Artus et al., 2023) and the potential of sediment loss caused by beach cleaning with heavy machinery (Simeone et al., 2022), municipalities in southern Catalonia have implemented less strict measures for the removal of banquettes. This region has prioritized tourism, its main economic driver, over the preservation of shoreline accumulations, despite their role as indicators of coastal environmental quality linked to adjacent seagrass meadows (Cantasano, 2021). Increasing tourism and globalization have been associated with long-term threats to beach sustainability (Alola et al., 2021), underscoring the need for management strategies that reconcile ecological functions with tourism. The Ecological Beach Model in Lazio, Italy, promotes two restrictive practices for banquette management: on-site preservation and temporary or partial displacements, with the latter restricted to areas within the same beach to maintain a closed sediment system and avoid sand loss (Manca et al., 2013). In this context, sustainable coastal management requires municipalities to recognize the sediment retention and permeability functions of banquettes, as highlighted in this study, as their removal may accelerate coastal erosion.

Furthermore, when positioned or maintained near the shoreline, banquettes may be considered a nature-based solution (NBS). A recent laboratory study using a mimic banquette demonstrated its capacity to limit wave run-up during erosive waves on a sandy beach, thereby preventing the erosion in the upper part of the beach (Astudillo-Gutierrez et al., 2025). Other measures may encompass the potential commercial utilisation of *Posidonia oceanica* accumulations, emulating the GE.RI.N project (Cappucci et al., 2015), which investigates the temporary utilisation of seagrass material as a filling medium for outdoor beach furniture during periods of peak tourist attendance. Following utilisation, the residual biomass is returned to coastal zones during periods of low beach occupancy, thereby maintaining its ecological function while supporting circular management strategies. Moreover, the Ecological Beach Model also facilitates scientific dissemination by providing technical guidelines on *Posidonia oceanica* and its cycle to beaches, municipalities, and schools (Rotini et al., 2020). Similar projects aimed at preserving banquette accumulations are being carried out in the Mediterranean area, such as RES MARIS in Sardinia, Italy, POSBEMED in Spain, France, Italy, and Greece, and POSBEMED 2 in Balearic Islands, South Spain, Cyprus, France, Italy (Sardinia), Greece, and Croatia (Manfra et al., 2024).

The removal of *Posidonia oceanica* results in the elimination of the sediment accumulated within the banquette (Astudillo et al., 2023; Simeone et al., 2022; Simeone and De Falco, 2013). In the case of Pixavaques Beach, our investigation reveals that the shoreline banquette retains an average of 9.17 kgm^{-3} of sediment. These values are significantly lower than those reported in previous studies. Simeone et al. (2022) documented sediment accumulations in banquettes ranging from 78 to 339 kgm^{-3} on the Sardinian coast, while Astudillo et al. (2023) measured values between 114.8 and 138.7 kgm^{-3} in the same study area. This disparity is primarily attributed to the location of the banquette along the active shoreline, where continuous wave exposure leads to ongoing sediment washing. In contrast, the older banquette, located further inland and characterized by more deteriorated leaves, experiences limited wave interaction and receives additional sediment input through wind transport (Nordstrom et al., 2011). Furthermore, the sediment retained in the banquettes was finer than that of the bare sand, which is consistent with findings by Simeone and De Falco (2012) and Astudillo et al. (2023), who reported that upper banquette layers accumulate sediments that are similar to or finer than those on the beach, while heavier particles tend to settle at the bottom of the banquette.

The response of coastal managers in Catalonia to beach erosion has been characterized by reactive measures, focusing on preparing the beaches for tourism. This approach has involved the use of beach nourishment as a remedial measure, rather than adopting a long-term perspective (Jimenez et al., 2011). Pixavaques Beach has been subject to this measure and is undergoing periodic nourishment to compensate for the ongoing sand loss. One of the consequences of this process is an increase in the median grain size of the beach sediment. The D_{50} value was 0.175 mm and the *Sr* was 0.128 mm 15 years ago (CIIRC, 2010). The results of this study demonstrate that these values have increased to 0.259 mm and 0.892 mm, respectively, indicating a significant shift in sedimentation. The material is now classified as moderately sorted, rather than very well sorted. Research by Bujan et al. (2019) indicates that an increase in the sediment size results in an elevation of the slope as a morphodynamic response of the coast. This aligns with observations at Pixavaques Beach, where the average slope measured across five transects has increased to 0.101, compared to 0.04, 15 years ago (CIIRC, 2010). In addition, nourishing non-native sediments to the beach may alter the profile, affecting the conditions for both aeolian transport to the dunes and interstitial fauna (Jackson et al., 2010).

The *P* measurements observed in the sand (1.84 MPa) and banquette (1.68 MPa) samples were similar and are within the range of resistances measured by cone penetration tests performed in dense sand under laboratory and field conditions. As reported in Tufenkjian et al. (2010), the *P* values ranged from 0.8 to 2.1 MPa at depths of 0.2 to 0.4 m. Similarly, Hsu et al. (2009) reported that *P* values between 1.3 to 2.4 MPa at a depth of 0.15 m, using a hand-operated penetrometer in compacted sand from field campaigns. In contrast, the penetration depths were considerably higher in the banquettes than in the sand (Figure 8). In sand, the maximum penetration depth reached 20 cm, whereas in the banquettes it extended up to 75 cm.

Fine sands exhibit known behaviour, with upper layers that are less dense and more susceptible to sediment remobilization processes. The sand becomes more compact at greater depths, resulting in greater resistance to penetration (Stark et al., 2012). In contrast, the nascent banquette with a high permeability value represents a complex structure that is dynamically constructed, transformed, and deconstructed in response to its interaction with waves and trapped sediments. This structural heterogeneity contributes to the irregular sediment retention within the banquette layers. Additionally, its permeability allows water to infiltrate the structure, mobilizing deeper sediments and potentially causing partial burial of the banquette at the bottom (Astudillo-Gutierrez et al., 2025). This process initiates the anchoring of the banquette, forming a foundation from which the structure can grow vertically under conditions of seagrass remains availability. As the structure developed, it evolved into a natural barrier capable of preventing overtopping by waves lower than its height. Furthermore, due to its high permeability, it effectively dissipates wave energy by reducing run-up, thereby enhancing the protection of the upper beach zone against erosion (Trogu et al., 2023; Passarella et al., 2020; Passarella, 2019; Vacchi et al., 2017).

The heterogeneity of the banquette has been corroborated by measuring the penetration resistance. The banquettes exhibited high variability in *P* at the close measurement point. However, there was agreement between the maximum resistance and the amount of sediment retained by the banquette. Transect 1 (T1) retained the lower amount of sediment. Figure 8B shows that none of the measurements in the banquette sample area reached their maximum penetration resistance values, and the maximum resistances in this transect are located at greater depths. The highest penetration resistance values were observed in the banquette samples area of transects T3, T4, and T5 (Figures 8F, H, J). These values are consistent with the high sediment content obtained within each of them. Despite these results, it is not possible to provide precise values for the amount of sediment retained as a function of its resistance to penetration. However, it can be inferred that if the maximum resistance to penetration at a specific depth within the banquette is comparable to that of the bare sand, this zone likely contains a higher quantity of sediment. In this regard, the use of a manual penetrometer could be valuable for the controlled removal of accumulations, aiming to minimize the impact of heavy machinery, which often causes over-excavation and removes a significant portion of the sand of the beaches.

The significantly higher permeability of *Posidonia oceanica* banquettes compared to bare beach sand (16.41 cm/s versus 0.051 cm/s) highlights their important yet often overlooked role in protecting the coastline from erosion. Unlike sand, banquettes act as dynamic, porous barriers that dissipate wave energy through enhanced infiltration. Even when mechanically compacted, banquettes remain more permeable than the surrounding sand. The implications of the permeability for coastal dynamics are poorly understood in the banquette structures.

Studies such as Jacobs (2011) and Mohr et al. (2021) suggest that permeability may be a crucial factor in erosion processes, closely linked to sediment properties such as bulk density and fines content, which affect threshold shear stress. A beach with higher permeability allows for greater infiltration, resulting in a significant reduction in backwash flow because greater flux can infiltrate inside the beach during the run-up phase (Saponieri and Damiani, 2015). Furthermore, authors such as Mohr et al. (2021) and Bisschop et al. (2010) indicate that an increase in permeability value results in a reduction in the erosion rate of the sediments. Despite its importance on the coast, experimental studies quantifying the relationship between permeability and sediment erosion resistance are scarce. This is largely due to the difficulty in measuring or estimating permeability, especially in surface layers (Mohr et al., 2018). In the case of banquettes, the interaction between their organic matrix and trapped fine sediments is complex, forming a heterogeneous structure that optimizes permeability while retaining sediments. This dual role is critical for shoreline protection and is a function that typical beaches without banquette accumulation or retired accumulations often fail to fulfil.

Building on this understanding, our findings demonstrate spatial variability: nascent banquettes exhibit the greatest permeability, whereas older, sand-rich deposits are less permeable yet still outperform bare sand. This gradient could form the basis of predictive models of beach morphodynamics, particularly in storm situations, where infiltration capacity can reduce the erosion. To this end, the permeability parameter of the banquette should be incorporated into numerical models, as has been done for gravel beaches, which are characterized by high permeability (Soloy et al., 2024; Jamal et al., 2014; Williams et al., 2012). Soloy et al. (2024) demonstrated the influence of permeability on beach profile dynamics, showing that high permeability values promote berm formation, while low permeability values contribute to erosion processes.

6 Conclusions

This study provides novel insights into the formation, distribution, and implications of *Posidonia oceanica* banquette accumulations along the southern coast of Catalonia, thereby contributing to the contextualization of their role in Mediterranean beach dynamics. The primary findings are outlined below:

- The presence of *Posidonia oceanica* meadows in shallow waters is a key factor influencing the development of coastal accumulations. Along the southern coast of Catalonia, where significant wave heights typically range between 0.4 and 0.8 m, the banquette accumulations are most frequent when the meadow is at depths less than 5 metres. Conversely, regions devoid of seagrass meadows or characterised by seabeds exceeding 5 metres in depth demonstrate a reduced propensity for the formation of accumulation. While the local wave regime plays an important role in the relationship between banquette accumulation presence and seagrass depth, anthropogenic stressors such as eutrophication, coastal development, and vessel anchoring can also lead to meadow degradation and plant mortality. This degradation has been shown to increase the amount of detached seagrass material available for coastal deposition, thereby influencing both the formation and distribution of these structures. Further research is required to validate the findings of this study, with a focus on assessing future scenarios involving beach banquette accumulation under projected sea level rise associated with climate change.
- Banquettes exposed to continuous wave action accumulate less sediment than those positioned at the backshore. The accumulated sediment characteristics in the upper part of the banquettes are typically a size finer than those representative of the bare beach.
- Penetration resistance (*P*) provides a practical and efficient method for identifying zones of maximum sediment accumulation within the banquette. Peak *P* values, similar to those observed in bare sand, indicate areas of deposition. This methodology also allows for the estimation of the depth of the banquette by measuring the distance of penetration where *P* is at its maximum value.
- The permeability parameter is an important factor to consider in these ecosystems. The banquette located closest to the shoreline exhibits a higher permeability than those farther offshore, although the latter still exceed the permeability of bare sand. This enhanced infiltration capacity is the key to effective erosion protection, giving these accumulations a clear competitive advantage over similar beaches without a banquette.

This study provides significant insights into the characteristics of banquette-type accumulations and underscores the necessity to safeguard these ecosystems on the beach. One of the most persistent challenges for beach managers is the maintenance of banquettes. Despite the well-documented adverse effects of mechanical cleaning, including the loss of sediments and subsequent beach erosion, this practice persists. One potential alternative for continued tourism on these beaches would be to disseminate information about the importance of maintaining these ecosystems and to restrict the removal of banquettes from the beach. The generation of sustainable economic alternatives that enable the utilisation of *Posidonia oceanica* accumulations without their removal from the coastal system, and, where feasible, their reuse as natural coastal protection during periods of increased erosion, also should be a strategic for coastal managers. These approaches are consistent with nature-based solutions and contribute to both shoreline resilience and local economic development.

Further research is required to deepen our understanding of banquettes, particularly regarding their interaction with waves and their influence on beach morphodynamics. This encompasses both field observations, such as those carried out in Mallorca (Spain) and Sardinia (Italy), and laboratory experiments aimed at quantifying their erosion protection capacity. The findings of these studies could be extrapolated to other Mediterranean regions where banquettes occur, including France, Greece, Croatia, Tunisia, Algeria, and Morocco. Additionally, evaluating parameters such as the permeability of these structures could offer valuable insights into their effectiveness in mitigating beach erosion.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

CA-G: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. EP-F: Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. VG: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Visualization, Writing – review & editing. JS: Conceptualization, Funding acquisition, Methodology, Project administration, Visualization, Writing – review & editing. TL: Conceptualization, Methodology, Visualization, Writing – review & editing. CM: Conceptualization, Funding acquisition, Methodology, Project administration, Writing – review & editing. XS-A: Conceptualization, Methodology, Visualization, Writing – review & editing. AS-A: Conceptualization, Funding acquisition, Methodology, Project administration, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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