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Earth-Surface Processes in the Anthropocene: Human Impact, Climate Change and Geomorphological Responses

Fractal Analysis, Morpho-Sedimentary Aspects and Coastal Vulnerability in Mediterranean Islands: A Novel Approach

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ABSTRACT

Mediterranean islands are increasingly threatened by climate change and growing tourism pressure, making the understanding of their coastal dynamics essential for sustainable management. This study investigated modern coastal dynamics and vulnerability on the islands of Procida (Tyrrhenian Sea, Italy) and Mykonos (Cyclades, Greece) through an integrated approach combining (1) two-dimensional fractal analysis, (2) granulometric and morphoscopic analyses of beach sediments and (3) coastal exposure assessment using geographical and effective fetch analyses. The methodological resources applied were (1) 2D-fractal analysis, (2) granulometric analysis of beach sediments, morphoscopy of quartz and silicate grains, (3) meteomarine climate and geographical fetch analysis. After performing physiographic subdivisions of the coastal perimeter of the studied islands, it was possible to compare and quantify their fragility. Our results indicated that the Mykonos shoreline has higher geometric complexity, as indicated by both the box-counting fractal dimension ($D_b = 1.15$) and the correlation fractal dimension ($D_c = 1.17$), than Procida ($D_b = 1.09$; $D_c = 1.12$), with Procida being more susceptible to uniform wave impact and possible extreme events. The greater vulnerability of Procida Island was also corroborated by the sedimentological analysis, which indicated a homogeneous classification of slightly gravelly sand in a highly energetic, constantly changing environment. The integrated methodological framework proved effective for assessing coastal vulnerability and morphodynamic behaviour in Mediterranean island environments and may support future coastal monitoring and management strategies.

1 | Introduction

Coastal environments are part of a natural system directly affected by interactions among the lithosphere, hydrosphere and atmosphere, as well as by terrestrial, aeolian and marine processes (Komi et al. 2022). Climate change, particularly the ongoing rise in sea levels at multiple scales and the intensification of human pressure, is increasingly compromising coastal zones by triggering coastal erosion and deforestation (Quesada-Ruiz et al. 2023; D'Aniello et al. 2026). It is also associated with

extreme events that lead to environmental imbalance, which occur more frequently and with greater magnitude. Among the main factors contributing to this problem are the increasing use and occupation of land, the growth of the tourism industry and population growth (Nicholls et al. 2016; Lämmle, Perez Filho, Donadio, Arienzo, et al. 2022; Karditsa et al. 2024). Thus, the elements associated with human activity, combined with geomorphological processes occurring on natural timescales, have caused several negative environmental impacts (Alevizos and Stamatopoulos 2016; Donadio et al. 2018; Rizzo et al. 2022).

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Approximately 41% of the European population lives near the coast, leading to rising urbanization and rapid growth in the tourism industry (Collet et al. 2013; Komi et al. 2022). Among the various types of coasts, those with sandy beaches have the highest concentration of recreational activities. They are among the most geomorphologically complex and, due to their greater sensitivity, are continuously altered by interactions between natural and anthropogenic factors (Davenport and Davenport 2006; Mentaschi et al. 2018). According to Vousdoukas et al. (2020), 13.6 to 15.2% of sandy coasts worldwide could be severely eroded by 2050, increasing to 35.7%–49.5% by the end of the century. These combined pressures have intensified coastal degradation, increasing erosion, habitat loss and the vulnerability of coastal communities to extreme events and sea-level rise.

Island environments deserve particular attention because they constitute socio-ecological systems characterized by limited land availability, strong dependence on coastal ecosystem services and high exposure to climate- and marine-related hazards (Baldacchino 2004; Kelman 2020). Their geographic isolation, restricted sediment supply and concentration of infrastructure and economic activities along narrow coastal zones increase their sensitivity to shoreline changes, coastal erosion and sea-level rise. In the Mediterranean, where tourism represents one of the main economic drivers, these pressures are further intensified by seasonal population growth and competing demands between environmental conservation and coastal development. Consequently, understanding coastal morphodynamics in island settings is essential not only for advancing geomorphological knowledge but also for supporting sustainable coastal management and strengthening the resilience of these socio-ecological systems undergoing environmental change (Folke 2006; Baldacchino 2018).

Research carried out in different sites and with diverse methodological approaches allowed a better understanding of these dynamics and the importance of coastal environments, like coastal hazard assessment (De Pippo et al. 2003), beach morphodynamics (Evelpidou et al. 2012; Lämmle and Bulhões 2019), paleoenvironment evolution (Emmanouilidis et al. 2020; Souza et al. 2020, 2022) and anthropogenic pressures (Silva et al. 2021; Lämmle, Perez Filho, Donadio, Moreira, et al. 2022; Rizzo et al. 2022). However, even with the existence of some studies (Andreadis et al. 2021; Quesada-Ruiz et al. 2023; Karditsa et al. 2024; Ferrer and Herrera 2024; Novikova et al. 2025), there is a lack of this kind of study in insular areas, which makes the present research both fundamental and innovative in understanding island littoral dynamics using a novel methodological approach. The geomorphological processes observed on the islands' coasts differ from those on the continental coast due to several geographic factors and multiscale processes, which require specific studies to be understood properly (Oliveira and Barboza-Pinzon 2025).

After carrying out a field mission in the Tyrrhenian and Aegean Seas, two case studies with distinct geomorphological processes were selected: the islands of Procida, Italy and Mykonos, Greece. Both are characterized by high global tourist demand and significantly higher population density during the summer than at other times. However, the exacerbated increase in human pressure on the coastal zone of these islands is reducing the original natural zones and causing the so-called 'coastal compression',

where important habitats, coastal processes and ecosystem services, among others, are confined in narrow zones or even disappearing, compromising the anthropic carrying capacity of beaches (Carboni and Russino 2013; Emmanouilidis et al. 2022).

Preserving the environmental quality of these beaches requires a better understanding of their morphosedimentary dynamics, particularly under increasing pressures from climate change, sea-level rise and tourism. Such knowledge is essential for supporting coastal adaptation and sustainable management strategies in Mediterranean island environments (IPCC 2018; Koukousioura et al. 2025). Thus, this study aims to understand and compare the morphosedimentary aspects of the islands of Procida and Mykonos, located in areas with distinct processes and forms but similar challenges in coastal management. For the first time, the methodological procedures adopted consisted of (1) 2D-fractal analysis to obtain the quantitative index of the geometric shape of the islands, (2) granulometric analysis of beach sediments, morphoscopy of quartz and silicate grains to understand the morpho-sedimentary aspects and genetic-depositional environment and (3) meteomarine climate and geographical fetch analysis to identify the coastal exposure and vulnerability.

The integration of quantitative and qualitative approaches provides a comprehensive framework for understanding coastal morphodynamics and vulnerability in Mediterranean island environments, offering scientific support for coastal conservation and sustainable management.

2 | Study Area and Environmental Settings

The study area comprises the Island of Procida, located in the Tyrrhenian Sea in southern Italy, close to the islands of Ischia and the Island of Mykonos, in the Cycladic Islands of Greece, near the islands of Naxos and Tinos, in the Aegean Sea (Figure 1). Despite their distinct morphological and sedimentary contexts (Kokkalas and Aydin 2013; Aucelli et al. 2022), these islands share similar environmental issues and challenges within the coastal zone, as the main attraction and local economy are based on beach tourism. According to the classification based on Köppen's climate formula (Köppen 1936), modified by Trewartha and Horn (1980) and Kottek et al. (2006), which classifies the climate of a site from a strictly thermal point of view, both islands are characterized by a Csa type: a subtype of the Mediterranean climate (Donadio and Fortelli 2020).

The Island of Procida rises on the inner continental shelf, north-west of the Gulf of Naples, within the volcanic district of Campi Flegrei (Phlegraean Fields), specifically in the western sector (Mattei et al. 2024). The Phlegraean Fields are a complex, poly-crateric area of about 100 km², characterized mainly by monogenic volcanic cones (Aucelli et al. 2022). Procida is precisely set on a structural high of this area, and this Horst continues the mainland of the Campanian Plain with an anti-Appennine trend (Putignano and Schiattarella 2010). The structural arrangement on which the volcanic activity of the Island of Procida was based is directly connected to that of the Gulf of Naples and to the extensional structures that affected it. These structures consist of NW-SE Appennine and NE-SW anti-Appennine fault families.

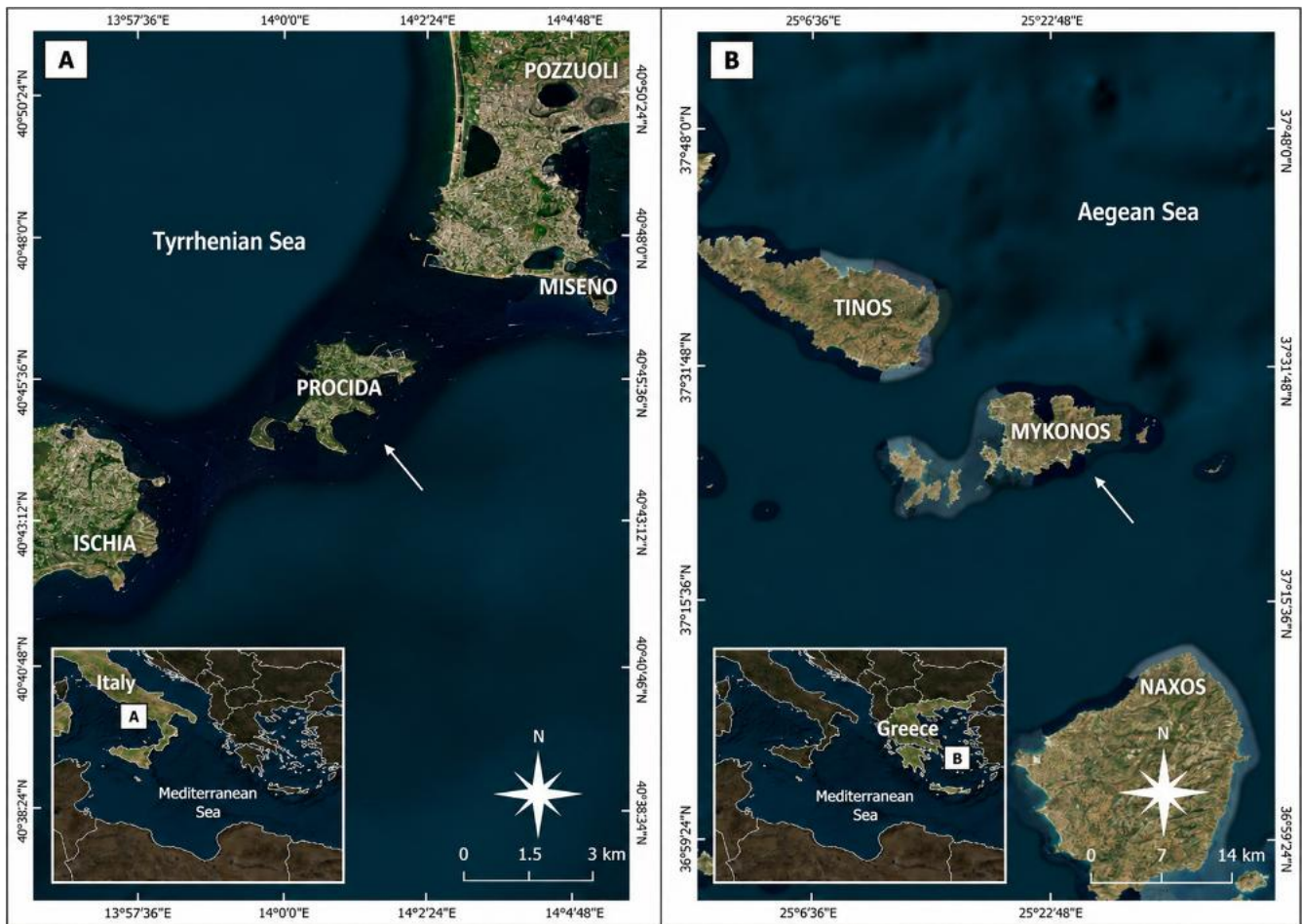


FIGURE 1 | Location of the study area. (A) Position of the Island of Procida in Italy and the Tyrrhenian Sea, with the Island of Ischia to the southwest, and the town of Pozzuoli and Cape Miseno to the northeast. (B) Position of Mykonos Island in Greece and the Aegean Sea, with the islands of Tinos to the northwest and Naxos to the south. The geographic coordinate system is WGS84. Basemap: ESRI—Environmental Systems Research Institute (2025).

From a geomorphological perspective, Procida measures approximately 3 km in length and 2 km in width; its top is flat, suggesting that the main geomorphological hazards are coastal in origin. The morphology of the island is predominantly subhorizontal, with the maximum elevation at Terra Murata, at ~55 m above sea level (a.s.l.).

The coast of Procida is characterized by semicircular bays, some of which are relics of craters, pocket beaches and beaches at the foot of cliffs, as well as numerous subvertical cliffs (Perrotta et al. 2010; Aucelli et al. 2022). The formation is therefore the result of several geological events: Pleistocene–Holocene pyroclastic eruptions in the Phlegraean Fields and late Quaternary sea-level fluctuations. In terms of use and occupation, Procida has a fixed population of ~10 000 inhabitants and offers relatively diversified tourism, with a focus on both historical and cultural heritage, as well as beach tourism, primarily in the summer (Figure 2).

According to Gazzola et al. (2023), the Cycladic Massif, where is located Mykonos Island, belongs to the Hellenides (Hejl et al. 2002; Papanikolaou 2009, 2013), which is part of the alpine orogenic belt and forms a roughly E–W trending orogen in the eastern Mediterranean region, following the curved shape of the active

Hellenic Subduction zone in the southern Aegean (Jolivet and Brun 2010; Ring and Layer 2003). This complex is characterized by metamorphic and igneous rocks and Quaternary sediments, with igneous outcrops in much of the island (Denèle et al. 2011). The hypsometry is characterized by smooth, mountainous relief, with a maximum elevation of 373 m a.s.l.

In terms of use and occupation, Mykonos (~10 000 fixed inhabitants) is a classic case of a Mediterranean island that was traditionally occupied by small rural and fishing villages, but in recent decades has become an island focused almost exclusively on tourism, with strong aesthetic regulations to preserve its charm (Lialios 2024). There are areas of natural and architectural protection, with urban regulations to maintain the Cycladic style (Blatsiou 2017). Much of the coast and some higher areas are occupied by hotels, resorts, villas and holiday homes, providing the basis for tourism on the island (Figure 2). Furthermore, in addition to the geological-geomorphological complexities of the islands and their associated processes, the common scenic beauty of the beaches on both islands, as well as the importance of maintaining their environmental quality, stand out. This is because their degradation, driven by various factors, can decline, reducing tourist interest and, consequently, the local economy.



FIGURE 2 | Beaches where sediment samples were collected on the islands of Procida and Mykonos. Chiaia and Ciraccio beach (PR-1 to PR-5), and Ornos, Little Venice and Old Port beaches (MK-1 to MK-3). The codes at the top represent the sediment samples collected (see Table 2 and Figure 3). Photo by L. Lämmle.

Procida and Mykonos were selected as representative case studies because they share key characteristics common to many Mediterranean islands, including a strong dependence on coastal tourism, increasing anthropogenic pressure and high exposure to coastal hazards. At the same time, they differ markedly in their geological setting, shoreline morphology and sedimentary environments, providing an opportunity to evaluate the proposed methodology under contrasting geomorphological conditions. This combination allows the robustness and applicability of the integrated approach to be assessed across distinct island morphodynamic settings.

3 | Materials and Methods

3.1 | Fractal Analysis 2D

Bidimensional (2D) fractal analyses of the coastal perimeters of the Procida and Mykonos islands were conducted for the first time and compared in the morphosedimentological scope. This

methodology has been successfully applied in coastal lagoons within the context of morphoclimatic processes (Barra et al. 2024), providing important insights for island environments, as both share polygonal geometry and are subject to coastal and oceanographic processes over time. In this sense, the aim is to determine whether the geometry and repetition of island shapes indicate an erosive trend or stability along the coast. To calculate the fractal dimension, Google Earth Pro satellite images from 2022, at a scale of approximately 1:5000 and in the WGS84 UTM geographic coordinate system, were used in a GIS (QGIS v.3.28.10) to delimit the coastal perimeter for each island (Table 1). The extracted georeferenced point coordinates are filtered to remove duplicates, uniformed to a 1000x1204 pixel dimension, converted to black and white and binarized. Then, the files were input to a software program to compute 2D-fractal dimension through the correlation integral termed G-P algorithm (Grassberger and Procaccia 1983):

$$C(R) = 2 / n(n-1) \sum_{i=1}^n \sum_{\substack{j=1 \\ j \neq i}}^n \Theta(R - |X_i - X_j|) \quad (1)$$

TABLE 1 | Features of Procida and Mykonos present-day island shores, from satellite images of GoogleEarth Pro: A, island surface area; Coastline size in kilometres; Maximum Island length; Maximum Island width. The fractal dimension of Procida and Mykonos shorelines was calculated using the box-counting (D_b) and correlation integral (D_c) methods: R^2 , correlation coefficient pertinent to box counting before the slash and correlation integral after it. See (Figure 7) for the island's geometry.

Island	A (km ²)	Coastline perimeter (km)	Maximum length	Maximum width	D_b	D_c	R^2
Procida	4.21	19.63	2.63	3.16	1.09	1.12	0.99
Mykonos	86.29	94.42	11.87	10.21	1.15	1.17	0.99

In Equation (1) Θ is the Heaviside step function whose value is 0 for $n < 0$ and 1 for $n \geq 0$, n is the number of points available and X_i the set of coordinates of the i -th point, $2/[n(n-1)]$ is the normalization factor representing the number of pairs such that $C(R)$ tends to 1 for R that tends to infinity. If the n points of the aggregate have a fractal distribution, then:

$$C(R) = k R^D \quad (2)$$

or, equivalently, on a log-log scale graph:

$$\log(C) = \log(k) + D \log(R) \quad (3)$$

where $C(R)$ is the cumulative frequency distribution of all the distances between the points, k is a constant and D is the fractal dimension. The correlation integral (1) counts the number of pairs of points whose distance falls within a set distance each time doubled. We processed 2500 XY georeferenced points representing the Procida shoreline and 3000 points representing the Mykonos shoreline, at a density of 100 to 250 points per linear kilometre. We used Equation (1) as well as the box-counting algorithm (Turcotte 1997; Saa et al. 2007) through the software Fractalyse v.3 (Vuidel et al. 2016) to calculate the fractal degree D_b :

$$D_b(s) = \lim_{r \rightarrow 0} \left(\frac{\ln N(r)}{\ln \left(\frac{1}{r} \right)} \right) \quad (4)$$

where the s is the length of an object, $N(r)$ is the number of boxes with the same side length r covering that object and $(1/r)$ is the scaling factor. Equation (4) counts the number of boxes of a grid occupied by at least one point with grid size doubled each time, plotted in a graph of $\log(N(r))$ versus $\log(r)$. If a fractal distribution exists, the plotted linear regression yields a straight line with slope D . Both methods compute the area clustering of the points analysed and allow us to determine a fractional dimension that quantifies the irregularity in the distribution of all points along the shores of the investigated islands. They also allow calculation of the scaling region within which the property of scale invariance holds, i.e., the property assimilating a short stretch of the shore, when extended, to a longer one. Advantage of applying Algorithm (1) rather than (4) is in the high level of confidence ($R^2 > 99\%$) reached in the scaling region computation (Mazzarella and Tranfaglia 2000; De Pippo et al. 2003; D'Alessandro et al. 2006; Donadio et al. 2015, 2019), even if the correlation dimension (D_c) is generally lower, $\sim 5\%$, than the box-counting one (D_b). For this reason, we report both results obtained by Equations (1) and (4), even though we consider the first one more reliable (Table 1).

In this sense, two complementary fractal indices were calculated in this study: the box-counting dimension (D_b), obtained using the box-counting algorithm and the correlation dimension (D_c), obtained using the Grassberger–Procaccia correlation integral. While D_b quantifies shoreline geometric complexity based on the scaling relationship between occupied grid cells and grid size, D_c estimates the spatial correlation among shoreline points and is generally considered a more robust measure of fractal scaling because it is less sensitive to grid discretization.

To calculate the fractal dimension of the shorelines and identify the range of distances within which the coordinates of each point of the forms follow the fractal Equation (3), we plot on a log-log diagram the number C of pairs of points with a distance smaller than R , as a function of R . The smallest usable distance is set to the linear resolution of 10 m and is gradually increased by a factor of 2. The best fit of the regression line of the least-squares of $\log(C)$ on the $\log(R)$ is obtained for distances between $4 \div 512$ and $2 \div 1024$ km for the box-counting and between $7 \div 429$ and $13 \div 729$ km for the correlation integral, with a fractal dimension D equal to the topological dimension of a line.

3.2 | Sites Identification and Granulometric Analysis

Beach sediments were collected at 5 points on the island of Procida and 3 points on the island of Mykonos, totaling 8 sediment samples (Figure 3). In Procida, the samples PR-1 to PR-3 were collected in Ciraccio Beach, and PR-4 and PR-5 Chiaia Beach; in Mykonos, the sample MK-1 was collected in Ornos Beach, MK-2 in Little Venice Beach and MK-3 in the Old Port Beach zone. All sediment samples were collected from the beachface (foreshore), within the active swash zone, to ensure comparable hydrodynamic conditions among the sampled beaches. The criteria used to choose the points were the level of anthropization of the beaches (selecting the most sought-after, considered more attractive in the tourist context and with a higher presence of urban structures), morphological aspects (beaches with different landscapes) and exposure to sea waves and currents.

All samples were analysed in the Sedimentology Laboratory of the Department of Earth Sciences, Environment and Resources (DiSTAR) at the University of Naples Federico II, Italy. Samples were mechanically quartered after drying in an oven at 105°C for 24 h. An amount of 100 g of each sample was fractioned from very coarse sand ($2-1 \text{ mm}/-1-0 \phi$) to clay ($<0.002 \text{ mm}/>9 \phi$). For standard laboratory granulometric analysis, a series of stacked ASTM sieves with a 0.5ϕ interval was used. The

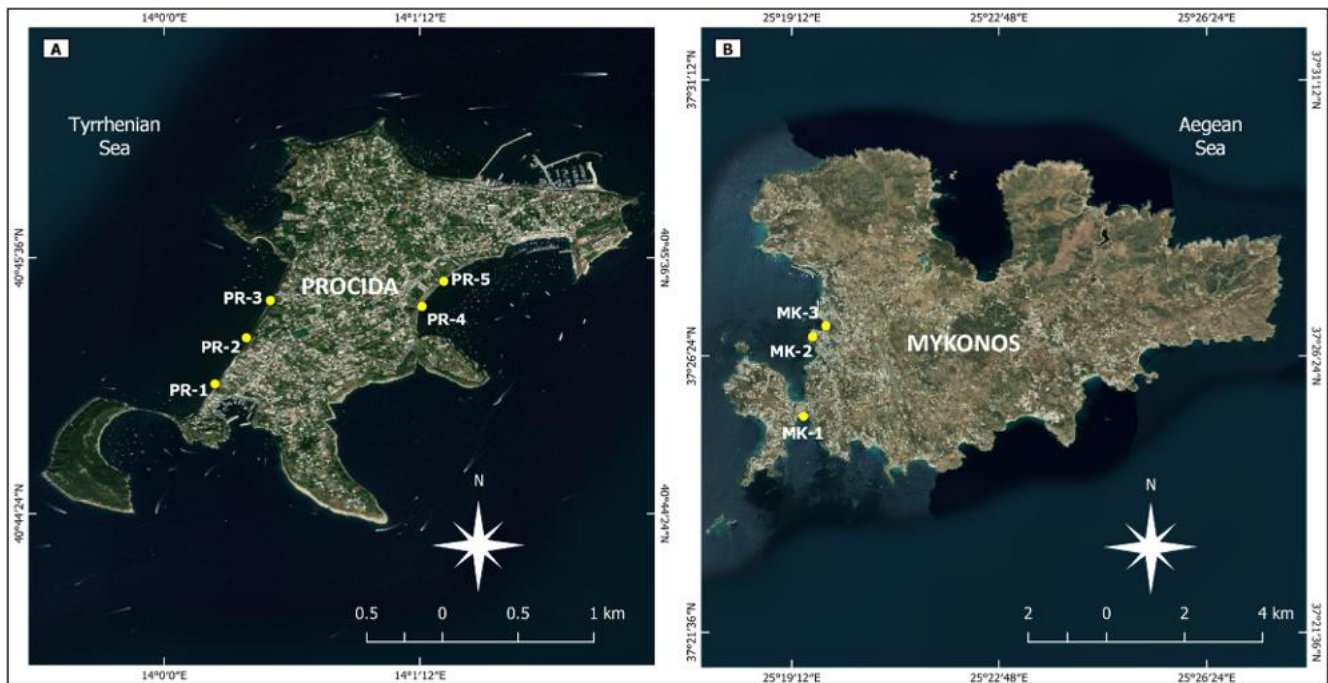


FIGURE 3 | The sampling sites (yellow solid circles) along the littoral of Procida and Mykonos islands.

technical procedures involved sieving with openings of the mentioned diameters and using a pipette to separate the clay and silt fractions (Belloni 1969).

Subsequently, the values were classified by Folk and Ward (1957) to evaluate the hydrodynamics and grain texture associated with the transport and deposition of the surficial cover during the Late Holocene. The software Gradistat v.9 was used to calculate grain-size parameters (mean size, sorting, skewness and kurtosis) using the method of moments (Swan et al. 1978), and the results are presented on the ϕ scale. The method of moments is used to calculate statistics based on a normal distribution of metric size values (Krumbein and Pettijohn 1938; Blott and Pye 2001).

3.3 | Morphoscopic Analysis and Genetic-Depositional Environment

An analysis of the shape of individual grains can provide valuable information about their transport processes, as it reveals how angular grains of distinct shapes are modified by abrasion and solution, for example. Because it involves measuring individual grains, it has not received as much attention as grain size. Nonetheless, it has proven important for complementing and contributing new data to discussions (Pettijohn et al. 1973).

The main properties analysed are roundness and shape. Roundness provides information about the grain's abrasion history. Current concepts, largely developed by Wadell (1935) and Krumbein (1934), also led to the creation of the first chart to estimate this measurement. The shape reflects the hydraulic processes involved in grain transportation, as it determines the ratio of surface area to volume, indicating how easily the material can be entrained by hydraulic action (Pettijohn et al. 1973).

The sphericity of a grain also plays a crucial role in morphoscopic analysis; it is a quantitative parameter, alongside roundness, that measures the equal dimensionality of a body. Powers (1953) developed a scale based on two sets of images of grains of varying sphericity, while the Rho scale of Folk (1955) was based on logarithmic intervals of the Powers scale. Later proposed by Sneed and Folk (1958), the maximum projection sphericity is the ratio of the particle's cross-sectional area to its maximum projection area.

Beach environments are characterized by continuous wave reworking, which promotes sediment abrasion, sorting and rounding, resulting in higher textural maturity than in many other depositional settings (Bird 2008). In general, grain roundness and mean grain size reflect the intensity of wave action and the sediment transport history, with more energetic beaches tending to contain better-rounded and texturally mature sediments.

In these granulometric fractions, 100 granules of quartz and silicate (K-feldspar and Na-plagioclases) for each sample, in total 1200 grains, representing the most resistant to abrasion, were selected and classified into three prevailing categories, according to Angelucci and Palmerini (1964), Pennetta et al. (2016), Arienzo et al. (2020) and Delogu et al. (2024): NA, not abraded, but transparent and angular; BT, translucent blunt, with subrounded to rounded edges; RO, well rounded opaque grains. The number of granules for each class is processed using Tri-Plot v.1.4 (Graham and Midgley 2000) to obtain percentages and a triangular diagram with the three classes (NA, BT, RO) at the vertices.

3.4 | Coastal Exposure Assessment Using Geographical and Effective Fetch

Coastal exposure was assessed through geographical and effective fetch analyses. Initially, the coastline of each island was

subdivided into Coastal Physiographic Units (CPU) according to Valente et al. (2014), considering shoreline orientation, headlands, coastal morphology and sediment transport boundaries. The centroid of each CPU was then used as the reference point for fetch calculations.

Geographical fetch was calculated in QGIS v.3.28 using the Fetch plugin, which measures the unobstructed distance over water in 5° directional intervals. Subsequently, effective fetch was calculated using the formulation proposed by Milano (1977), which weights the geographical fetch according to wind incidence angle. The resulting values were processed in Microsoft Excel to generate polar diagrams representing the spatial variability of coastal exposure. This procedure allowed comparison of wave exposure among different coastal sectors of both islands and supported the interpretation of sedimentological and geomorphological patterns.

Observing the open access data on [Climate-Data.org](https://climate-data.org) based on the European Centre for Medium-Range Weather Forecasts (ECMWF), a model characterized by more than 1.8 billion data points and a resolution of 0.1–0.25 grid, a similar average annual temperature emerges for both islands, respectively, of 17.7° for the Island of Procida and 17.8° for the Island of Mykonos. The average annual rainfall is higher on the island of Procida, at 952 mm, while it is 379 mm on Mykonos (Theocharatos 1978). This difference is linked to a topographical feature of the Island of Procida: because of southwest winds, it is in the orographic shadow of Mount Epomeo, a volcano-tectonic horst on the nearby Island of Ischia. The predominant wind direction is N-NE, with a relative humidity rate of 71%.

Characterizing the exposure conditions of the coastlines was achieved by analysing the islands' geographic and effective fetch. The first represents the open sea surface on which the wind blows with a constant direction and intensity (at least four knots for 6 h a day), capable of generating significant wave motion. The second, the effective fetch, indicates the effective extension of the portion of the sea in which the transfer of energy from the wind to the sea occurs with the genesis of the waves. To calculate the effective fetch, first of all, the traversing sector and the relative geographic fetch were defined, then the following formula of Milano (1977) was applied:

$$F_{eff} = \frac{\sum F_{geo_i} \cos^2 \alpha_i}{\sum \cos \alpha_i} \quad (5)$$

where F is the geographic fetch of the i -th direction (in km), and α_i is the angle that the i -th direction makes with the wind.

Furthermore, it is characterized by the particularity that the sediments have movements confined within the unit itself or in any case exchanges with the outside to a negligible extent, except in rare cases in which the capture of sediments occurs by the work of submarine canyons very close to the shoreline or in the presence of streams and rivers which, during exceptional floods, cause their rapid evacuation towards the open sea (funnelling). The CPSU is smaller and further subdivides the coast within the same CPU.

The CGU further simplifies the coastal units, characterising them based on the morpho-evolutionary processes and geo-indicators present. Procida falls within the NW limit of the CPU of the Gulf of Naples and has been further divided into 3 CPU considering its morphology, the type of coasts between low, high and technocoasts (De Pippo et al. 2008), and its geographical exposure (see Figure 7). The presence of important maritime infrastructures characterises the coast facing north (3 CPU) and the one to the east (2 CPU), which alternates between cliffs and semicircular bays featuring pocket beaches. In comparison, the one facing W (1 CPU) is characterized on the edges by high coasts and in the central area by the beach of Ciraccio and Chiaiolella.

The same principles were adopted for the island of Mykonos. In particular, the north coast is indented and characterized purely by cliffs. The coast exposed to S-SE is instead characterized by alternating cliffs and bays with pocket beaches. Finally, the coast exposed to W presents an essential maritime infrastructure at the edge of the cliffs.

4 | Results

4.1 | Fractal Analysis

The fractal analysis of the island coastlines revealed that Mykonos had higher values for both box-counting dimensions ($D_b = 1.15$) and the correlation dimension ($D_c = 1.17$) than Procida, which had lower values ($D_b = 1.09$; $D_c = 1.12$) (Table 1). This suggests greater geometric complexity in the Mykonos shoreline, which is more fragmented and articulated, with numerous headlands, caves and indentations (Figure 4). Procida, although smaller in area and perimeter, shows a relatively dense coastline with a high perimeter-to-area ratio but lower fractal irregularity. The slight variability between the box-counting and correlation dimension values in both islands, with D_c higher, indicates a strong spatial correlation among coastal points, especially in Mykonos. This pattern was confirmed by the high coefficient of determination ($R^2 = 0.99$), suggesting a robust linear fit across multiple spatial scales in both methods and providing high confidence in the fractal estimates.

4.2 | Sedimentological Analysis and Genetic Depositional Environment

The particle size distribution (Figure 5A, Table 2) of most samples (PR-1 to PR-5 and MK-2) is classified as slightly gravely sand, i.e., composed almost entirely of sand (98.7% to 99.9%), with traces of gravel (0.1% to 1.3%) and absence of silt and clay. Only two samples (MK-1 and MK-3) are classified as sandy gravel, with much higher gravel contents (60% and 35.2%, respectively). The average grain size (M_z , in ϕ) ranged from -1.125ϕ (MK-1, indicating very coarse grains) to 1.166ϕ (PR-4, indicating finer grains within the sand fractions). The PR samples present values close to 0, indicating a predominance of medium sand.

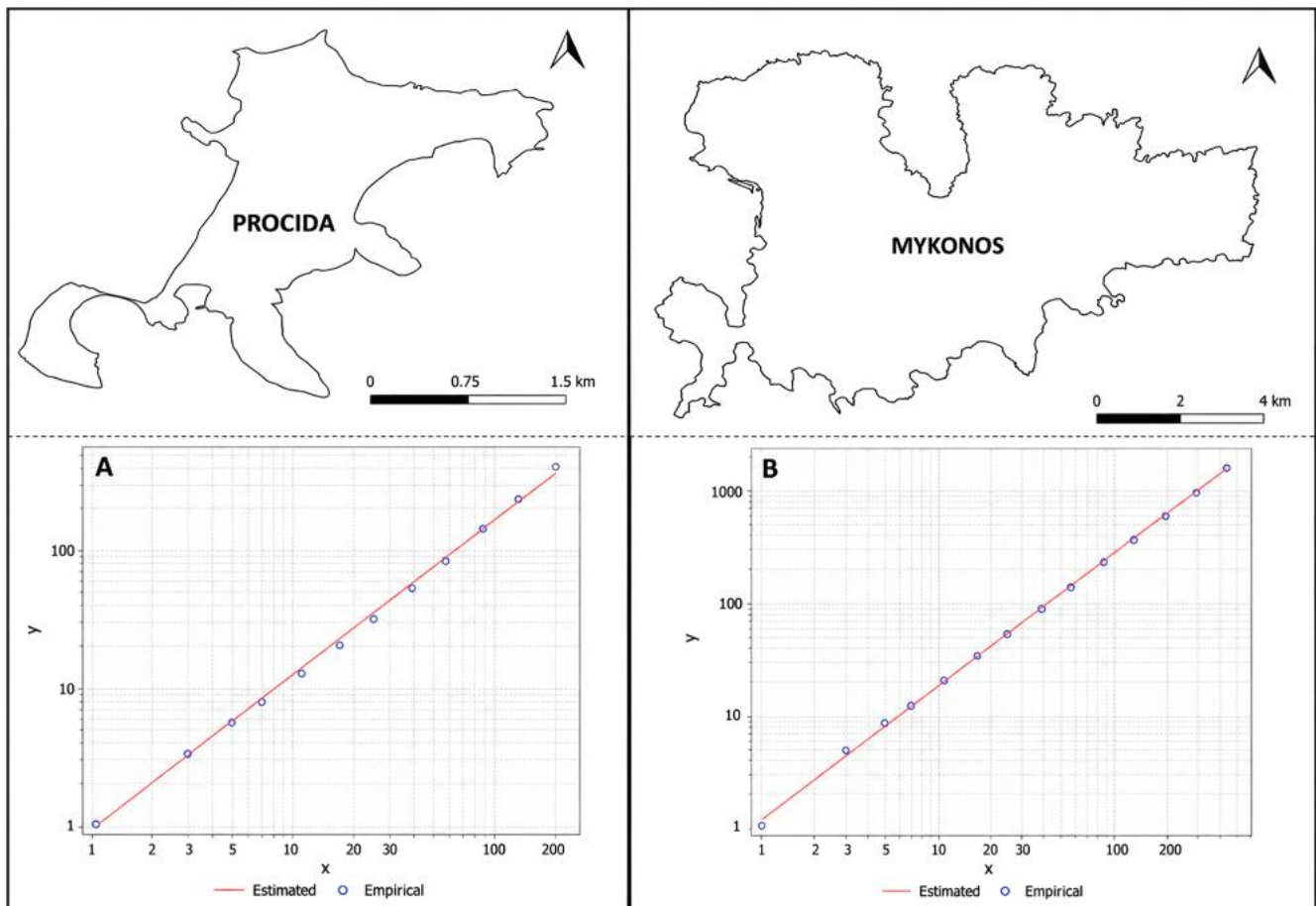


FIGURE 4 | Geometry of the emerging part of the island of Procida and Mykonos, represented by the delimitation of the coastline using Sentinel 2 satellite imagery, for subsequent processing and 2D fractal analysis. The geographic coordinate system used is WGS84.

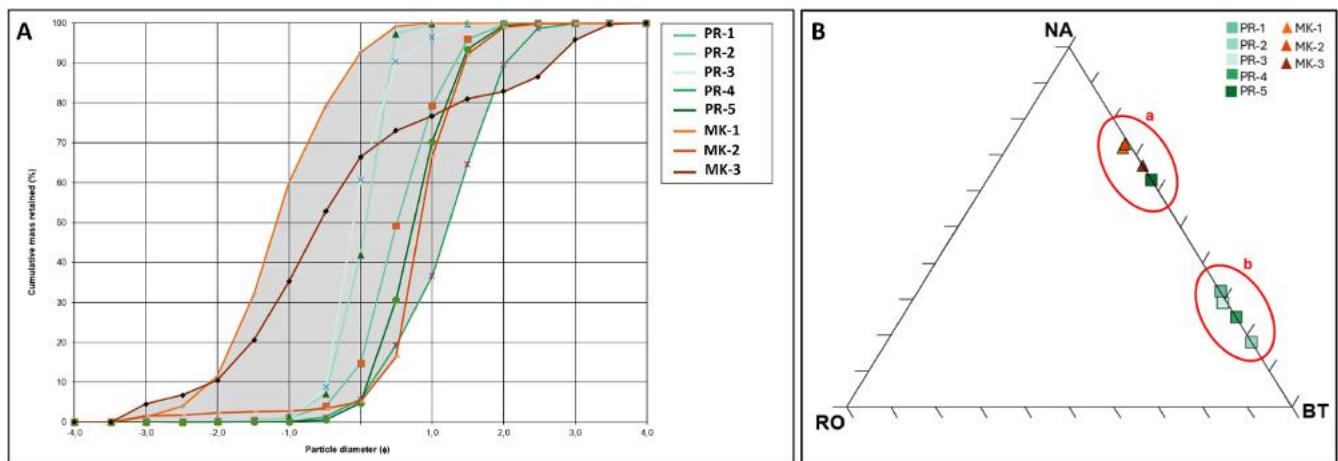


FIGURE 5 | (A) Granulometric spindle of the cumulative frequency curves of the samples collected at Procida and Mykonos sites. The grey area represents the hydrodynamic energy that deposits the sediments. (B) Distribution of morphoscopic classes of the various samples from different locations: NA, not abraded; RO, rounded opaque; BT, blunt translucent. Most samples show BT (b) and NA shapes (a).

Regarding the statistical particle size parameters obtained from Folk and Ward (1957) – Table 2, the standard deviation (σ) ranged from 0.357 ϕ (PR-2, well sorted) to 1.852 ϕ (MK-3, very poorly sorted). Most PR samples showed good sorting, whereas MK-3 showed greater particle-size heterogeneity. Asymmetry (S_{KI}) ranged from -0.235 (PR-2, slightly asymmetric for coarser

particles) to 0.306 (MK-3, slightly asymmetric for finer particles). Most samples showed values close to 0, indicating symmetry or slight asymmetry. Kurtosis (KG) varied between 0.880 (PR-2) and 1.224 (MK-2), with values close to 1 indicating a normal distribution of particles; values below 1 indicating a flatter distribution.

TABLE 2 | Geographical localization of samples, elevation, grain size distribution, granulometric classification, mean size, Mz, standard deviation, σ , skewness, S_{KI} , kurtosis, K_G and morphoscopic analysis of sediments.

Sample #	Latitude N	Longitude E	Elevation m	Gravel		Silt + Clay		Mz	σ	S_{KI}	K_G	Morphoscopy %		
					%							NA	BT	RO
Classification ¹														
PR-1	40°45'00.38"	14°00'14.33"	0.2	0.4	99.6	0.0	Slightly gravelly sand	-0.043	0.443	0.218	1144	32	68	0
PR-2	40°45'11.89"	14°00'22.34"	0.1	1.3	98.7	0.0	Slightly gravelly sand	0.030	0.357	-0.235	0,880	18	82	0
PR-3	40°45'23.99"	14°00'30.00"	0.1	1.2	98.8	0.0	Slightly gravelly sand	0.555	0,569	0,068	1002	29	70	1
PR-4	40°45'22.34"	14°01'12.50"	0.2	0.1	99.9	0.0	Slightly gravelly sand	1166	0,737	-0,128	0,932	25	75	0
PR-5	40°45'28.64"	14°01'20.41"	0.2	0.1	99.9	0.0	Slightly gravelly sand	0,749	0,515	0,055	0,929	63	37	0
MK-1	37°26'55.44"	25°19'47.62"	0.1	60.0	40.0	0.0	Sandy gravel	-1.125	0.788	0.068	0.999	72	26	2
MK-2	37°26'44.11"	25°19'53.79"	0.1	2.8	97.2	0.0	Slightly gravelly sand	0.882	0.477	0.090	1.224	73	26	1
MK-3	37°25'21.02"	25°19'24.34"	0.1	35.2	64.8	0.0	Sandy gravel	-0.046	1.852	0.306	1.135	67	33	0

¹According to Folk and Ward (1957), $^2\phi = -\log_2 Q_{mm}$, NA, not abraded transparent; BT, blunt-edged translucent; RO, rounded opaque granule.

Three categories of grains were analysed (Figure 5B): NA (transparent non-abraded), BT (translucent blunt edges), RO (rounded opaque grains). Most grains are translucent with blunt edges (BT), ranging from 26% to 82%, while little or no presence of rounded opaque grains (RO), except for sample MK-1 (2%).

Regarding the Friedman (1967) and Martins (2003) diagrams (Figure 6), in the Friedman diagram (on the left), the samples from Procida are concentrated in the region associated with the beach environment. They are characterized by medium to fine grain size (Mz between 0.5 and 1.5 ϕ) and good to moderate sorting (σ_I between 0.4 and 0.7 ϕ). This grouping suggests that depositional conditions were dominated by marine processes, with sufficient energy to remove fine and coarse fractions, thereby favouring grain homogenization.

In contrast, the Mykonos samples show a more dispersed distribution. Sample MK-1 exhibits low sorting ($\sigma_I > 1.5 \phi$) and a coarser average grain size (Mz $< 0 \phi$), placing it in the fluvial environment area. Sample MK-2 occupies an intermediate position between the beach and dune zones, indicating a mixed influence of aeolian and coastal processes. Sample MK-3, on the other hand, with excellent sorting ($\sigma_I < 0.5 \phi$) and medium-to-coarse grain size (Mz close to 0 ϕ), is located in the typical area of aeolian dunes, an environment characterized by unidirectional transport and a high degree of sedimentary sorting.

The Martins diagram (Figure 6 on the right) corroborates these interpretations. The Procida samples show asymmetries near zero (S_{KI} between -0.2 and 0.2 ϕ), consistent with relatively stable marine environments, such as sandy beaches. In Mykonos, MK-1 shows a higher S_{KI} (close to 0.5 ϕ), typical of fluvial deposits, whereas MK-3 shows a slightly positive S_{KI} with low σ_I , reinforcing its association with an aeolian environment.

The results indicate that Procida presents a depositional system dominated by marine processes, with sedimentation controlled by wave energy, while Mykonos shows greater depositional complexity, with the combined action of fluvial, aeolian and coastal processes. This differentiation suggests variations in the sedimentary dynamics and morphology of the sampled areas, reflecting distinct environmental conditions between the two islands. The Procida samples (PR-1 to PR-5—squares) are concentrated in the beach area, with a good selection and average grain size consistent with the coastal environment.

The Mykonos samples (MK-1 to MK-3—triangles) are more dispersed, with MK-1 and MK-2 located close to or within the river area, indicating less sorting. MK-3 is closer to the dune area, with good sorting and coarser grains. The Procida samples cluster in the beach area, with S_{KI} values near zero, indicating a more stable marine environment. Additionally, it presents MK-1 with higher σ_I and higher S_{KI} , compatible with a river environment. MK-2 is in the transition environment between the beach and the dune. MK-3 has low σ and slightly positive S_{KI} (can be compatible with a dune), while Procida (PR) presents characteristics consistent with a coastal/marine environment, probably a beach, with well-sorted sediments and uniform grain size.

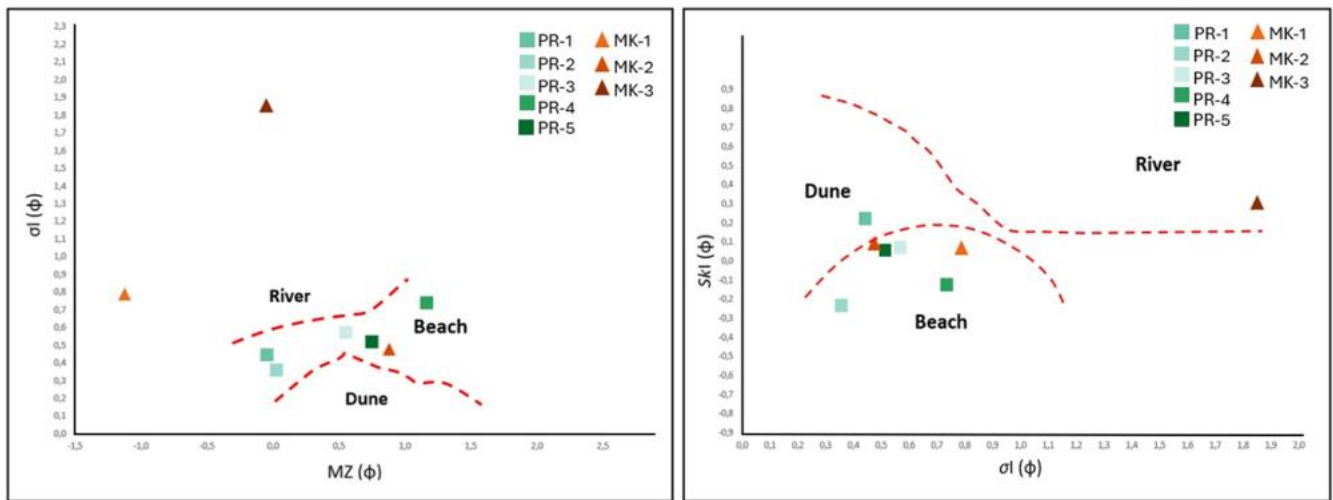


FIGURE 6 | On the left, Friedman's (1967) diagram based on the relationship between $\sigma_I(\phi)$ and $S_{KI}(\phi)$ for the classification of the environment of the same area. On the right, Martins' (2003) diagram is based on the relationship between $Mz(\phi)$ and $\sigma(\phi)$ for the classification of the genetic-depositional environment of samples from the islands.



FIGURE 7 | Subdivision of the Island of Procida and Mykonos into Coastal Physiographic Units, using software QGIS v.3.28.

MK-1 may be associated with a fluvial system. MK-2 represents a transitional environment. MK-3 presents typical features of an aeolian dune. This distinction suggests marked environmental differences between the two sites, with Procida presenting a more homogeneous depositional system (coastal beach), while Mykonos shows the action of multiple processes (fluvial, aeolian and coastal).

4.3 | Geographic and Effective Fetch

The three areas analysed on Procida and Mykonos Island exhibit distinct exposure configurations (Figure 7).

Figure 8A presents a preferential fetch orientation towards the west and southwest. The geographic fetch is quite restricted, suggesting the presence of barriers such as Corsica and the Italian

mainland. However, effective fetch is more open, indicating exposure to winds over long distances at sea, which contributes to the energy of the incident waves, mainly in the SW-W quadrants. Figure 8B shows a highly directional fetch pattern, with a predominance of narrow bands in the NW-SE quadrants. The geographic fetch shows significant variations, but the effective fetch is more concentrated, suggesting that the most energetic winds occur in specific sectors. This may indicate more sheltered areas or local wind channelling.

Finally, Figure 8C, located in an area with greater exposure to the Tyrrhenian Sea, presents the most significant development of geographic fetch. The effective fetch follows this pattern, indicating high exposure to waves generated by long-trajectory winds, especially in the southern and southwestern sectors. This suggests a significant energy potential for coastal processes, such as erosion and sediment transport.

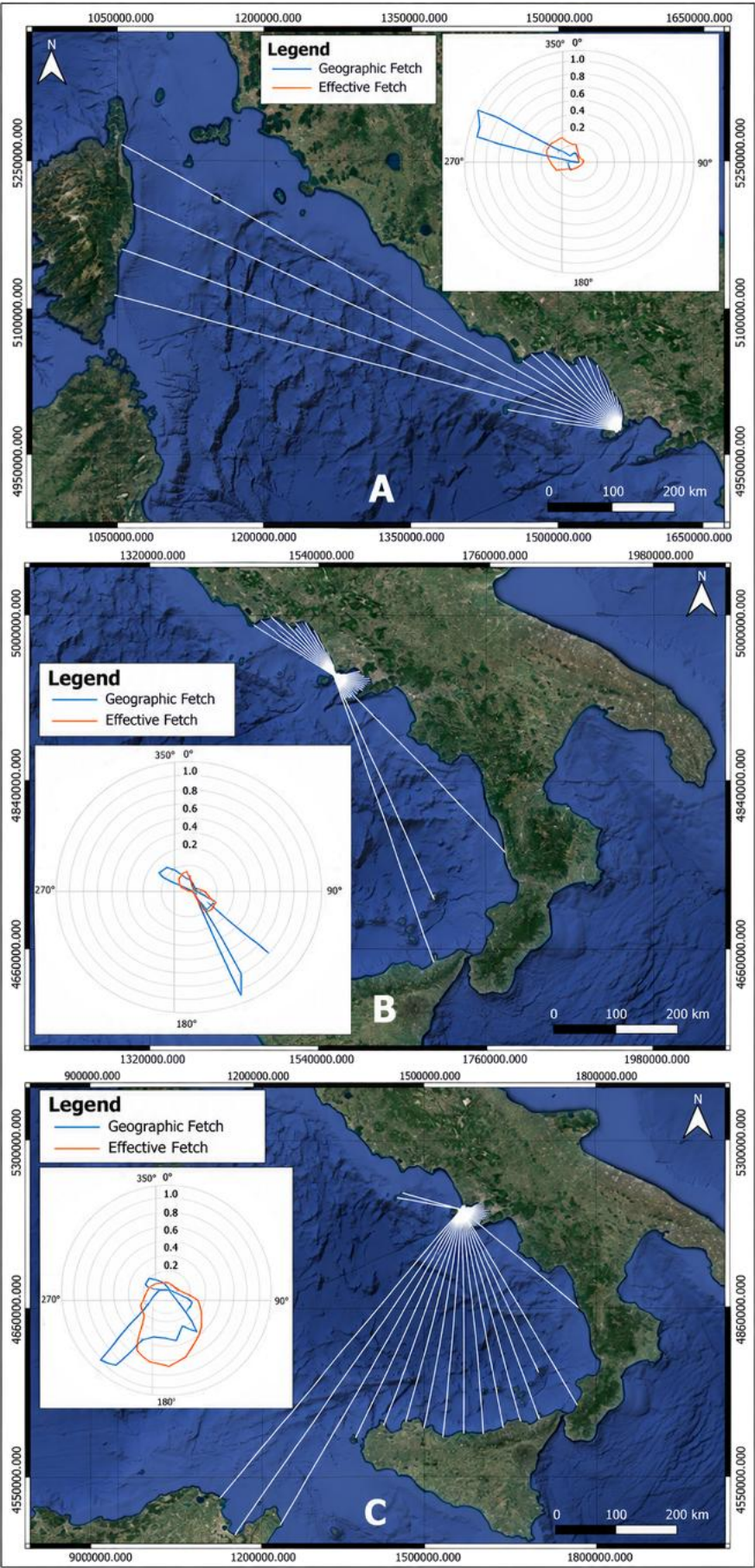


FIGURE 8 | Legend on next page.

FIGURE 8 | Geographical and Effective Fetch of the Island of Procida—CPU 1. (A) The wave motion is mainly generated by W-WNW, corresponding to the quadrants of the Mistral and Ponente winds. CPU 2 (B) The wave motion is generated by the SE and the WNW sectors, respectively, relating to the Scirocco and Ponente-Maestrale wind quadrants. CPU 3 (C) The wave motion is generated purely in the southern sector relating to the South, Libeccio and Scirocco winds. Fetch distances in the polar diagrams were normalized by the maximum geographic fetch value, resulting in dimensionless values ranging from 0 to 1, where 1 represents the maximum fetch distance (A: 1.0 = 450 km; B: 1.0 = 350 km; C: 1.0 = 400 km).

On the island of Mykonos (Figure 9A–C), the three points evaluated reveal very distinct exposure conditions, reflecting the complex morphology of the Greek archipelago. Figure 9A shows a wide opening to the north and northwest, reflecting both the geographic and effective fetch. The agreement between the two suggests the absence of significant barriers, allowing the action of long-trajectory winds. This configuration favours the formation of more energetic waves, which are characteristic of exposed environments.

Figure 9B shows greater asymmetry between geographic and effective fetch, with the latter being more restricted. This may be related to islands and underwater reliefs that limit wave development, even in directions with high geographic fetch. Thus, this area has partial exposure, with coastal processes generally more moderate. Figure 9C shows a very directed and limited effective fetch, indicating a relatively sheltered environment. The island's topography and nearby islets act as physical barriers, limiting the generation of large waves. This scenario is compatible with more stable and protected depositional environments, such as covers or internal beaches.

5 | Discussion

The islands of Procida and Mykonos have distinct geometric shapes. The values of the fractal dimensions (Table 1) indicate that Mykonos has a more complex and articulated coastline, as evidenced by its higher box-counting ($D_b = 1.15$) and correlation ($D_c = 1.17$) dimensions than Procida ($D_b = 1.09$; $D_c = 1.12$). Despite the distinct geological backgrounds of Procida and Mykonos, including their differing volcanic origins and sedimentary environments, fractal analysis reveals a noteworthy morphological convergence in the coastlines of the two islands. This geometry convergence indicates that, at the geomorphological scale, both islands respond to coastal-shaping processes in similar ways, despite their local environmental differences. This means that a higher fractal dimension indicates a greater capacity of coastal geometry to dissipate wave energy over a larger contact surface, potentially reducing erosive intensity at localized points. Conversely, a lower dimension may indicate greater vulnerability, as wave energy is less evenly distributed (more concentrated and consequently more intense). The slight difference between D_c and D_b across both islands, with D_c slightly higher, emphasizes that the spatial clustering of points (correlation structure) is even more pronounced than the box-counting method alone can reveal.

This morphological similarity suggests that, despite their unique local conditions, both island coasts follow shared principles of coastal morphodynamics. From a coastal management perspective, recognizing this convergence is important because it implies that strategies developed for one island, based on these common processes, could be adapted and applied to the other, with adjustments for local specifics. Ferrer and Herrera (2024)

identified similar aspects in the Canary Islands in Spain, highlighting and confirming the sensitivity and multi-risk factor of insular environments, mainly associated with exposure to storms and geomorphological connectivity (Sanromualdo-Collado et al. 2025). Ultimately, fractal analysis not only quantifies complexity but also provides an integrated framework to understand coastal vulnerability and resilience across different insular environments in the Mediterranean.

Regarding sedimentary aspects, the combination of predominantly sandy, well-sorted sediments and a low-complexity coastline in Procida implies a higher vulnerability to coastal erosion and sea-level rise. Volcanic Mediterranean islands with relatively uniform beach compartments commonly exhibit more homogeneous sedimentological characteristics and stronger local control by wave exposure and sediment availability (Aucelli et al. 2022; Gazzola et al. 2023). Additionally, the greater coastal vulnerability observed for Procida is consistent with recent studies highlighting that Mediterranean islands are particularly sensitive to sea-level rise, tourism pressure and reductions in sediment supply (Quesada-Ruiz et al. 2023; Karditsa et al. 2024; Ferrer and Herrera 2024). The coast's simplified morphology exposes it directly to waves, reducing its capacity for energy dissipation.

On the other hand, Mykonos, with coarser sediments, a significant gravel component and a more complex coastline, demonstrates greater physical resistance to wave action. The high fractal geometry promotes the dissipation of marine energy across multiple indentations, reducing erosion at isolated points. This means that although Procida and Mykonos differ in substrate composition and sediment characteristics, the coastal dynamics driven by wave energy, wind and currents induce comparable patterns of coastline development and adaptation. The shaping forces give rise to analogous fractal geometries that reflect the underlying processes of erosion, sediment redistribution and shoreline evolution. Similar patterns have been reported for Mediterranean islands, where lithological heterogeneity, rocky headlands and pocket beaches promote greater shoreline irregularity and spatial variability in sediment characteristics (Evelpidou et al. 2012; Poulos et al. 2015; Andreadis et al. 2021).

The morpho-sedimentary analysis enabled us to interpret key differences in coastal vulnerability based on sediment type, hydrodynamic processes and coastline complexity. The data indicates two distinct sedimentary and hydrodynamic contexts: the Procida Island PR samples (PR-1 to PR-5) are composed almost exclusively of sand (98.7% to 99.9%), with minimal gravel content (0.1%–1.3%) and no silt or clay. The classification as “slightly gravelly sand” and the average size (M_z) values near 0 (medium sand) suggest deposition in relatively high-energy environments, typical of beaches or transition zones near the coast. The good degree of sorting (σ between 0.357 and 0.737 ϕ) reinforces the hypothesis of an efficient transport agent, such as waves or ocean currents. The slightly negative

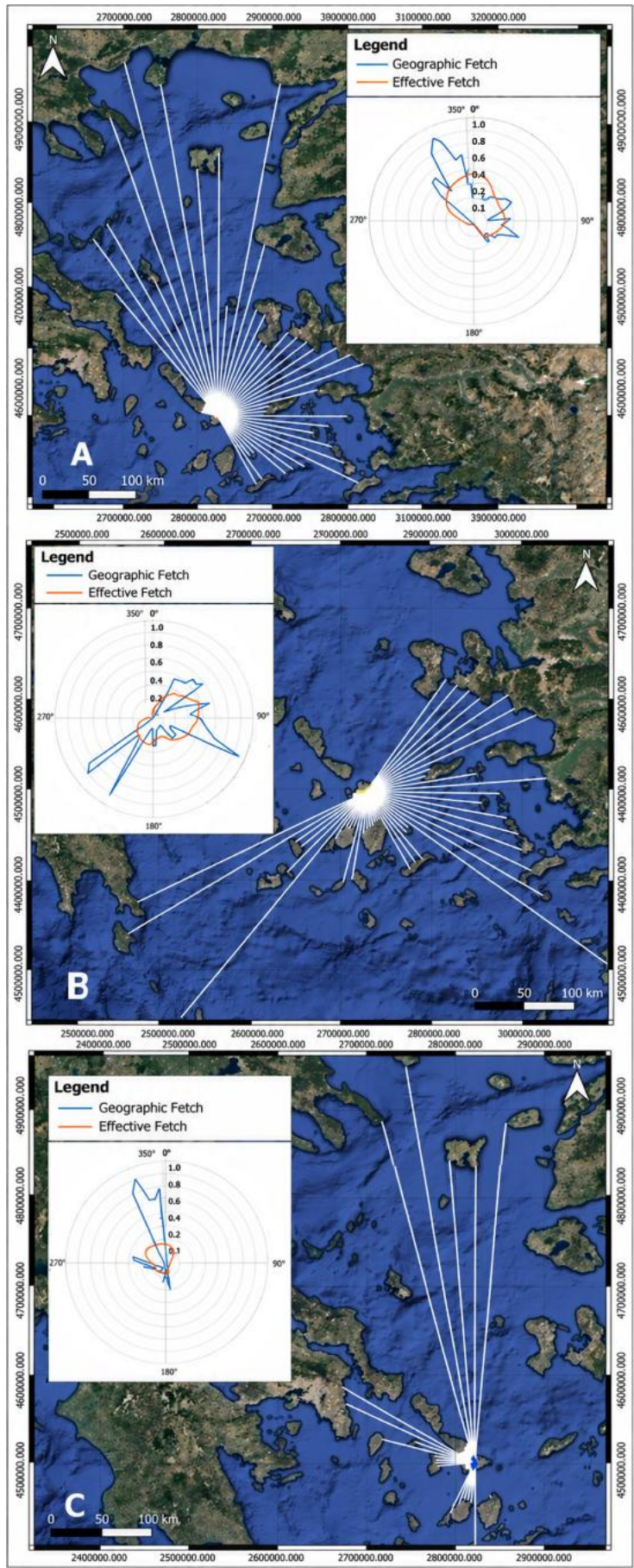


FIGURE 9 | Legend on next page.

FIGURE 9 | Geographical and Effective Fetch of the Island of Mykonos—CPU 1 (A) The wave motion is generated purely in the NW sector with a contribution also from sector E, corresponding respectively to the Tramontana-Maestrale and Levante winds. CPU 2 (B) The wave motion is generated purely in sector E relative to the Levante and Greek winds, but there is also a contribution from the SW with the Libeccio winds. CPU 3 (C) The wave motion is generated purely in the N sector relative to the Tramontana wind. Fetch distances in the polar diagrams were normalized by the maximum geographic fetch value, resulting in dimensionless values ranging from 0 to 1, where 1 represents the maximum fetch distance (A: 1.0 = 400 km; B: 1.0 = 350 km; C: 1.0 = 300 km).

asymmetry in some samples (PR-2 and PR-4) indicates a slight predominance of coarse particles, consistent with coastal reworking processes. The morphoscopy, with a high percentage of translucent, blunt-edged (BT) grains, suggests moderate to intense reworking typical of coastal environments.

In Mykonos, samples MK-1 and MK-3 have a high proportion of gravel (60% and 35.2%, respectively) and are classified as ‘sandy gravel’, while MK-2 is like PR (slightly gravelly sand). The mean size (M_z) of MK-1 (-1.125ϕ) confirms the predominance of very coarse sediments (coarse gravel). A high standard deviation in MK-3 (1.852ϕ) indicates a mixture of particles of various sizes, typical of high-energy, fast-deposition environments such as alluvial fans, gravel beaches or storm areas. Morphoscopy predominates slightly abraded (NA) grains, mainly in MK-1, suggesting relatively short transport or limited exposure to marine reworking processes, like in other Mediterranean islands (Avramidis et al. 2017).

The PR samples suggest deposition in a typical sandy beach environment, with continuous wave action sorting the grains. MK samples reveal a more heterogeneous mixture, with evidence of higher-energy environments and possible influence of episodic sedimentary events (e.g., storm currents or continental sediment input). Morphoscopy reinforced this interpretation, showing that rounding and abrasion vary with sediment transport and depositional environments. The differences in fractal dimensions between the two islands, Procida and Mykonos, are relatively small (Table 1), indicating that they share correlated modelling and geometric evolution processes.

The comparison between Procida and Mykonos shows that Procida is more exposed to westerly and southwesterly winds, with areas more susceptible to higher wave energy, especially in regions without significant geographic obstructions (as in point C). On the other hand, Mykonos presents a more complex exposure, shaped by the archipelago’s insular configuration. In general, Mykonos has more sheltered areas with reduced effective fetch, especially in the southern and eastern portions of the island, which favour sedimentation and coastal stability. These results are consistent with the previously analysed sedimentological data, which point to more aeolian and fluvial characteristics in Mykonos and predominantly marine characteristics in Procida. The interaction between coastal topography and regional wind patterns is a crucial factor in determining local morphodynamics and sedimentary processes.

The distribution, refraction and attenuation of wave energy along the coastline are strongly influenced by geometric complexity, which is effectively captured by fractal dimensions. In this way, fractal geometry not only reflects morphological patterns but also serves as a proxy for understanding how wave energy is absorbed, redistributed or amplified along insular

coasts. This reinforces the interpretation that small differences in fractal dimensions may translate into meaningful differences in coastal resilience under storm conditions and projected sea-level rise scenarios (Donadio et al. 2019, and references therein).

Human pressure, particularly related to tourism-driven urbanization, coastal engineering works (harbours, marinas and breakwaters), beach nourishment and shoreline stabilization, can locally modify the indicators calculated in this study, although it is unlikely to fundamentally alter the broader geomorphological trends controlled by geology and regional hydrodynamics, as highlighted by Poulos et al. (2015) in Lefkada Island, for example. Anthropogenic interventions may simplify or artificially regularize segments of the coastline (Andreadis et al. 2021), potentially lowering local fractal dimension values by reducing natural indentations, while sediment extraction, beach grooming or nourishment can modify grain-size distributions and sorting parameters. Infrastructure such as ports and protective structures may also alter effective fetch at a local scale by changing wave propagation and sediment transport pathways.

Considering the challenges and importance of island environments in the face of global change, comparing these two islands is a necessary starting point, as it addresses a knowledge gap and proposes an integrated, innovative methodological approach. Much remains to be done to understand the coastal dynamics of islands in general and to advance various methodological approaches. While this work presents a relatively limited spatial scope, focusing on two islands, it offers a novel methodological approach that can be replicated and adapted for any island or group of islands worldwide.

The integrated methodological framework adopted in this study proved effective for investigating coastal dynamics at the island scale. Fractal analysis quantified shoreline complexity, granulometric and morphoscopic analyses characterized sediment transport and depositional processes, while fetch analysis provided an objective measure of coastal exposure to wave action. However, the proposed approach is primarily intended to characterize present-day coastal conditions. Consequently, it does not directly account for temporal shoreline evolution, seasonal sediment variability or hydrodynamic processes derived from numerical modelling. These aspects should be considered in future studies to complement the present framework and provide a more comprehensive assessment of long-term coastal morphodynamics.

6 | Conclusions

The coastal vulnerability of both islands is controlled by the interaction among shoreline geometry, sedimentary characteristics and wave exposure. Although Mykonos exhibits a more

irregular coastline and greater morphosedimentary heterogeneity, Procida is characterized by a smoother shoreline, well-sorted sandy sediments and greater exposure to prevailing waves, making it more susceptible to coastal erosion and extreme events. These findings demonstrate that coastal vulnerability in Mediterranean islands is closely linked to local morphodynamic processes operating at different spatial scales.

The integrated analysis also identified sectors of greater fragility on both islands, providing valuable information for coastal management, particularly in the context of increasing tourism pressure, climate change and sea-level rise. Beyond identifying the greater overall vulnerability of Procida, the study highlights the importance of combining shoreline geometry with sedimentological and meteomarine parameters to support more effective management and adaptation strategies.

The multidisciplinary framework adopted through integrating fractal analysis, sedimentological and morphoscopic characterization and fetch analysis proved effective for assessing present-day coastal dynamics and vulnerability in Mediterranean island environments. As demonstrated in these two pilot case studies, this approach provides a robust and transferable methodology that can be applied to other insular and continental coastal systems. Future studies incorporating shoreline evolution, numerical wave modelling and long-term monitoring would further improve the understanding of coastal morphodynamic responses under increasing environmental and anthropogenic pressures.

Author Contributions

Luca Lämmle: conceptualization, fieldwork, formal analysis, investigation, methodology, validation, writing – original draft. **Archimedes Perez Filho:** funding acquisition, resources. **Vinicius Borges Moreira:** data analysis, validation, writing – review and editing. **Silvia Ilacqua:** conceptualization, data analysis, fieldwork, writing – review and editing. **Mariarca D'Aniello, Pavlos Avramidis:** validation, data analysis, writing – review and editing. **Bruno Araujo Torres, Leonidas Stamatopoulos:** formal analysis. **Carlo Donadio:** conceptualization, data analysis, methodology, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data will be available upon request to the corresponding author.

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