

Article

From Artificial Structures to Biogenic Habitats: Two-Year Ecological Responses to Eco-Engineered Reefs in a Tourism-Dominated Adriatic Sandy Coast

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Abstract

Sandy coastal ecosystems are among the most widespread yet ecologically simplified marine habitats, particularly where anthropogenic pressures and the scarcity of structurally complex habitats limit biodiversity. This study evaluated the ecological effects of eco-engineered submerged reefs deployed in 2021 along the sandy coast of Lido degli Scacchi (northern Adriatic Sea, Italy). Twenty-one fully submerged eco-engineered Tecnoreef[®] modules were installed within the gaps between existing detached breakwaters, introducing a highly porous and architecturally complex habitat into a shallow sedimentary environment. Benthic communities were monitored over two years through the assessment of soft-bottom infaunal and hard-substrate epifaunal assemblages. Community development on Tecnoreef modules was compared with that occurring on adjacent limestone breakwaters under both windward and leeward exposure conditions. Infaunal assemblages were primarily influenced by hydrodynamic exposure and showed limited differentiation between habitat types, although abundance and diversity increased around the submerged structures over time. In contrast, epifaunal communities exhibited marked temporal changes and developed compositions distinct from those observed on breakwaters. Among the taxa contributing most strongly to community differentiation was the reef-building polychaete *Sabellaria spinulosa*. The progressive establishment of this ecosystem-engineering species suggests that the eco-engineered modules provided favorable conditions for the early stages of secondary biogenic habitat development, although longer-term monitoring will be required to determine whether these developing habitats persist and evolve into stable ecological systems. Our results provide encouraging evidence that structurally complex submerged reefs can increase habitat heterogeneity and support the development of diverse benthic assemblages in highly modified sandy coastal environments. Although longer-term monitoring is required to assess habitat persistence and ecosystem-level effects, these findings highlight the potential of eco-engineered reefs as nature-based tools for supporting biodiversity enhancement and habitat development in tourism-dominated coastal landscapes.



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1. Introduction

The north-western Adriatic Sea, including the Emilia–Romagna and Veneto coasts, is characterized by one of the largest low-gradient sedimentary coastal systems in the

Mediterranean basin. Unlike the eastern Adriatic shoreline, where rocky reefs and natural hard substrates contribute substantially to habitat heterogeneity, this sector is largely dominated by sandy and sandy-muddy bottoms. The main natural exception is represented by the carbonate biogenic outcrops locally known as *tegnùe*, which form isolated hard-bottom habitats hosting diverse benthic assemblages and acting as biodiversity hotspots within an otherwise homogeneous soft-bottom environment [1,2].

The ecological structure of the northern Adriatic coastal seabed has been strongly influenced by long-term anthropogenic pressures. Among these, bottom-contact fisheries represent one of the most pervasive disturbances affecting benthic habitats and ecosystem functioning. Mechanical alteration of sediments caused by fishing gears can reduce habitat complexity, modify sediment characteristics, and negatively affect benthic biodiversity [3,4]. Along the Emilia–Romagna and Veneto coasts, hydraulic and mechanical dredges targeting the striped venus clam *Chamelea gallina* constitute one of the most widespread fishing activities [5]. The repeated passage of these gears continuously reworks the seabed, increasing sediment disturbance and limiting the establishment of stable benthic communities. Consequently, extensive coastal areas remain characterized by simplified habitats, low structural complexity, and reduced ecological resilience [6].

The restoration of degraded marine ecosystems has recently become a priority within both international and European environmental policies. The United Nations Decade on Ecosystem Restoration (2021–2030) identifies ecosystem restoration as a key strategy for reversing biodiversity loss and recovering ecosystem services [7]. Similarly, the European Union Nature Restoration Regulation (EU Regulation 2024/1991) establishes legally binding targets for restoring degraded terrestrial and marine ecosystems, requiring Member States to implement restoration measures across at least 20% of EU land and sea areas by 2030 and progressively expand restoration actions thereafter [8]. These policy frameworks highlight the need for innovative and scalable restoration approaches capable of enhancing biodiversity and supporting ecological recovery in heavily modified marine environments.

Within this context, artificial reefs (ARs) have become one of the most widely adopted tools for marine habitat restoration, fisheries management, and ecological engineering. Artificial reefs are intentionally deployed structures designed to increase habitat complexity, provide substrate for colonization, enhance biological productivity, protect vulnerable habitats, and support fisheries resources [9]. Their application has expanded worldwide over the last decades, encompassing objectives ranging from stock enhancement and biodiversity conservation to habitat restoration and coastal protection.

The Mediterranean Sea represents one of the regions where artificial reefs have been most extensively developed and studied. Since the 1970s, numerous reef systems have been deployed in Italy, Spain, France, and other Mediterranean countries. Fisheries enhancement and fisheries management have historically been among the principal objectives of Mediterranean reef programs [10,11]. In particular, anti-trawling reefs have been widely used to prevent illegal bottom trawling, protect sensitive benthic habitats, and promote the recovery of fish assemblages and benthic communities [11,12]. Italy has played a pioneering role in the development of artificial reef technologies and management approaches within the Mediterranean region, with several reef complexes deployed along its coasts, including the Adriatic Sea [13–15].

Despite this extensive experience, artificial reefs have rarely been considered as restoration tools for highly urbanized sandy shorelines primarily devoted to seaside tourism. Most Mediterranean reef projects have been developed in fishing grounds, marine protected areas, or seagrass habitats, whereas comparatively little attention has been devoted to heavily exploited sedimentary coastal environments where tourism represents the dominant socioeconomic activity [15]. This is particularly true along the north-western Adriatic coast,

home to one of Europe's most thriving summer beach tourism industries, where coastal management has traditionally focused on beach nourishment, shoreline stabilization, and erosion-control measures [16], while ecological restoration has received comparatively less attention.

In June 2021, the Emilia–Romagna Region implemented an experimental restoration intervention along the coast of Lido degli Scacchi (northern Adriatic Sea, Italy). The project involved the deployment of fully submerged eco-engineered barriers within the gaps between existing detached breakwaters, creating a network of structurally complex habitats within an otherwise homogeneous sandy environment. Unlike the adjacent coastal defense structures, which consist of compact limestone boulders, the submerged modules were specifically designed to maximize habitat complexity through a highly porous three-dimensional architecture characterized by cavities, crevices, and sheltered internal spaces. The intervention therefore provided a unique opportunity to evaluate whether eco-engineered habitats can support biodiversity development and ecological trajectories distinct from those associated with conventional coastal defense infrastructures.

The present study investigates the ecological role of these submerged barriers within a highly anthropized sandy coastal environment historically subjected to intense hydrodynamic disturbance and chronic seabed reworking caused by clam dredging activities. Specifically, the aims of this study were to: (i) assess the ecological effects of eco-engineered submerged reefs on benthic communities, evaluating changes in both soft-bottom infaunal and hard-substrate epifaunal assemblages; (ii) compare community development on newly deployed reef modules with that occurring on adjacent limestone breakwaters, in order to determine whether substrate architecture and habitat complexity influence colonization patterns; (iii) evaluate the potential of submerged reefs to increase habitat heterogeneity and function as biodiversity hotspots within an otherwise homogeneous sedimentary ecosystem; and (iv) assess the role of restoration-oriented artificial structures in promoting ecological recovery trajectories in tourism-dominated coastal landscapes. More broadly, the study provides one of the first evaluations of eco-engineered submerged reefs as a nature-based restoration solution for sandy Adriatic shorelines, contributing to the implementation of the EU Nature Restoration Regulation and the objectives of the UN Decade on Ecosystem Restoration.

2. Materials and Methods

2.1. Study Area and Artificial Barrier Deployment

The study was conducted off Lido degli Scacchi (44°43' N, 12°14' E), on the Emilia–Romagna coast of the northern Adriatic Sea (Figure 1a). The area is characterized by wide sandy beaches and shallow nearshore waters with gently sloping sandy bottoms.

As along much of the Emilia–Romagna coastline, coastal erosion is mitigated by emerged detached breakwaters constructed from stacked limestone boulders and arranged parallel to the shoreline (Figure 1b). In June 2021, twenty-one Tecnoreef modules were deployed within the gaps between adjacent breakwaters at approximately 3 m depth. The modules were arranged in an arc-shaped configuration, with the concavity facing the prevailing wave direction (Figure 1c).

The submerged barriers were constructed from Tecnoreef inert concrete plates (UNI EN ISO 14001:2004 [17] certified for Marine Artificial Reefs applications). Each pyramidal module consisted of 51 perforated concrete plates (120 cm long) arranged to form a highly porous three-dimensional structure characterized by holes, crevices, cavities, and sheltered internal spaces (Figure 1d). Each module was approximately 1.7 m high and had an 8 × 8 m square base.

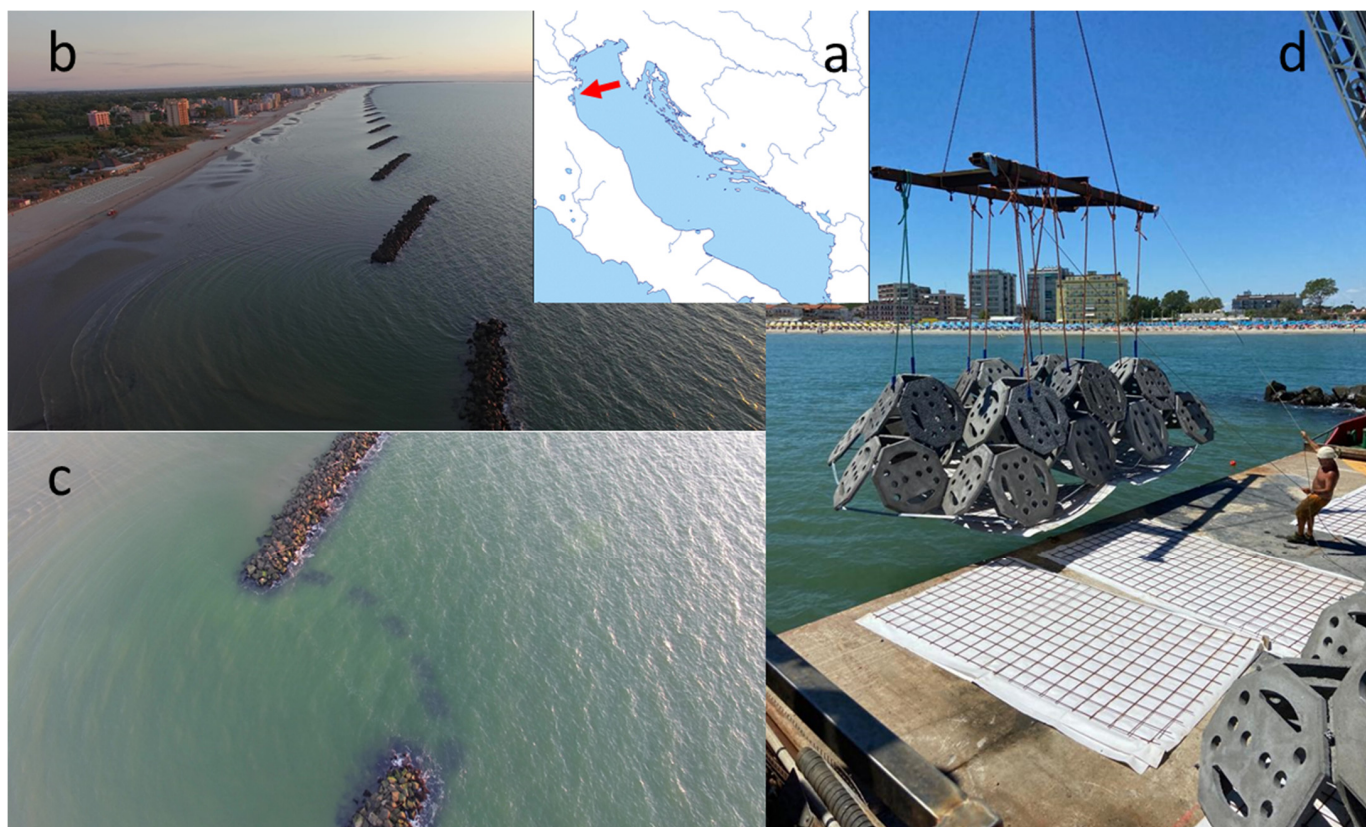


Figure 1. Study area and restoration structures. (a) Location of the study site along the coast of Lido degli Scacchi (northern Adriatic Sea, Italy); (b) emerged detached breakwaters constructed from stacked limestone boulders and arranged parallel to the shoreline; (c) submerged Tecnoreef barrier system deployed between adjacent breakwaters and arranged in an arc-shaped configuration with the concavity facing the prevailing wave direction; (d) pyramidal Tecnoreef module assembled from perforated concrete plates (map from <https://www.d-maps.com/conditions.php?lang=it>, accessed on 10 May 2026).

In contrast, the adjacent breakwaters consisted of compact quarried limestone boulders with comparatively limited internal void space. Consequently, the Tecnoreef modules differed markedly from the breakwaters in terms of structural complexity and habitat architecture, providing a suitable framework for evaluating the influence of substrate design on benthic community development.

2.2. Sampling Design and Benthic Community Assessment

To evaluate the ecological effects of the submerged restoration structures, a two-year monitoring program was conducted following their deployment. The first survey (T0) was carried out within a few weeks after installation, and subsequent surveys were performed after 12 and 24 months (T12 and T24, respectively). All surveys were conducted during the same season (July) to minimize the influence of seasonal variability on benthic community composition.

The study adopted a hierarchical sampling design. Three groups of Tecnoreef modules were selected within the restoration area, while three detached limestone breakwaters located in the same coastal sector were selected as control sites. These reef groups and breakwaters represented the primary spatial sampling units and were monitored throughout the study.

Because local hydrodynamic conditions were expected to influence benthic community development, each sampling unit was investigated separately on its windward and leeward

sides. Within each habitat type, exposure condition, and sampling period, replicate samples were collected to characterize local-scale variability in benthic assemblages. Environmental variables such as current velocity, wave energy, sediment grain size, and sediment organic matter were not measured concurrently with the biological surveys conducted in the present study. Consequently, hydrodynamic exposure was treated as a categorical factor (windward vs. leeward), based on the orientation of each sampling unit relative to the prevailing wave direction. Future monitoring of the restoration site will integrate biological surveys with quantitative environmental measurements to better identify the physical mechanisms driving benthic community development.

The resulting design included the fixed factors habitat (Tecnoreef vs. breakwater), exposure (windward vs. leeward), and time (T0, T12, and T24). The combined assessment of soft-bottom infauna and hard-substrate epifauna enabled the evaluation of both indirect effects of the submerged structures on surrounding sediments and direct colonization processes occurring on the newly created artificial substrates.

2.2.1. Soft-Bottom Infaunal Sampling

Sediment-dwelling assemblages were investigated in the sandy seabed adjacent to the artificial structures. At each sampling campaign, samples were collected from the windward and leeward sides of both Tecnoreef groups and control breakwaters.

Three replicate sediment samples were collected using a Van Veen grab (sampling volume: 4 L; sampling area: 0.035 m²). Replicates were obtained within a limited area surrounding each sampling unit in order to characterize small-scale spatial variability in the associated infaunal assemblages.

Sediment samples were sieved through a 0.5 mm mesh and preserved in ethanol for laboratory analysis. All macrozoobenthic organisms were sorted, identified to the lowest possible taxonomic level, and counted.

2.2.2. Epifaunal Sampling

The development of hard-substrate epifaunal assemblages was assessed through direct underwater sampling by SCUBA divers. At each survey, communities were sampled on the windward and leeward faces of both Tecnoreef groups and control breakwaters.

Sampling was performed using the standardized scraping (*grattage*) technique, widely adopted for the quantitative assessment of Mediterranean hard-bottom communities [18]. All organisms colonizing a 20 × 20 cm quadrat (sampling area: 0.04 m²) were removed using underwater scrapers and collected in sealed sampling bags.

Three replicate quadrats were sampled within each habitat–exposure combination. On Tecnoreef modules, samples were collected from representative external surfaces of the pyramidal structures, whereas on breakwaters, quadrats were positioned on submerged limestone boulders at comparable depth and exposure conditions.

In the laboratory, all specimens were sorted, identified to the lowest possible taxonomic level, and counted.

2.3. Data Analysis

For both infaunal and epifaunal assemblages, biodiversity was assessed using total abundance (N), species richness (S), Shannon–Wiener diversity (H'), and Pielou's evenness (J'). Shannon diversity was calculated using log₂-transformed abundances.

Prior to analysis, abundance data used for multivariate analyses were square-root transformed to reduce the influence of highly abundant taxa. The square-root transformation was specifically chosen as a moderate option to down-weight the influence of highly dominant species, thereby allowing intermediate and common taxa to contribute to the similarity patterns, while avoiding the excessive amplification of rare, transient species

that typically occurs with more severe transformations like $\log(x + 1)$. Assumptions of normality and homogeneity of variances for univariate descriptors were evaluated using Shapiro–Wilk and Levene’s tests, respectively. The effects of habitat (Tecnoreef vs. breakwater), exposure (windward vs. leeward), and time (T0, T12, and T24) on each univariate descriptor were tested using three-way factorial ANOVA. Significant effects were identified at $p < 0.05$. Analyses were performed using R software [19].

Temporal changes in community composition were investigated using Bray–Curtis similarity matrices calculated from square-root transformed abundance data. Non-metric multidimensional scaling (nMDS) was used to visualize patterns of similarity among samples. The goodness-of-fit of the ordinations was evaluated using Kruskal’s stress coefficient, with stress values < 0.20 considered acceptable for ecological interpretation.

Differences in community composition among habitats, exposures, and sampling periods were tested using permutational multivariate analysis of variance (PERMANOVA). The analyses were based on Bray–Curtis dissimilarities and conducted using 9999 permutations of raw data under a reduced model. Because repeated observations were collected from the same reef groups and breakwaters through time, temporal comparisons should be interpreted as repeated observations of the same sampling units rather than as fully independent temporal replicates. Permutations were performed without restriction because the study design was balanced and sampling units remained fixed throughout the monitoring period.

Similarity percentage (SIMPER) analysis was used to identify the taxa contributing most to observed differences among groups. The species listed by SIMPER are discriminating/characterizing taxa rather than true indicator species [20].

All multivariate analyses were conducted using PRIMER v7 with the PERMANOVA+ add-on package [20,21].

3. Results

3.1. Infaunal Communities

A total of 27 infaunal taxa were recorded throughout the study period. The assemblages were numerically dominated by the bivalve *Lentidium mediterraneum*, which accounted for the majority of collected individuals, followed by *Mactra stultorum*, *Tritia neritea*, *Ruditapes philippinarum*, *Donax semistriatus*, *Spio filicornis* and *Chamelea gallina*.

Univariate community descriptors showed differences between windward and leeward stations (Table 1). Total abundance was generally higher at leeward sites, whereas species richness, Shannon diversity (H'), and Pielou’s evenness (J') were consistently higher at windward stations. Diversity and evenness increased through time in both habitats, with the most pronounced trends observed at Tecnoreef sites. In contrast, leeward assemblages were characterized by lower diversity and stronger dominance by a limited number of taxa despite their higher abundances. Community descriptors indicate progressive community development throughout the monitoring period and highlight hydrodynamic exposure as a major source of variation in infaunal assemblages.

Univariate analyses revealed significant effects of habitat, exposure, and time on most community descriptors (Supplementary Materials, Table S1). Exposure was the strongest factor affecting species richness, Shannon diversity, evenness, and abundance. Time also significantly influenced all descriptors, while habitat significantly affected abundance, richness, diversity, and evenness. Significant habitat $\times$ exposure interactions were detected for abundance, richness, and evenness, whereas exposure $\times$ time interactions were significant for richness, diversity, and evenness. No significant three-way interactions were observed.

The nMDS ordination (Figure 2a) revealed a well-defined separation only between samples grouped according to exposure. Leeward stations (circled in red) clustered dis-

tinctly from windward stations, whereas substantial overlap was observed among habitat and time categories.

Table 1. Mean ($\pm$ SD) values of total abundance (N), species richness (S), Shannon–Wiener diversity (H' , $\log_2$), and Pielou’s evenness (J') for infaunal assemblages sampled at Tecnoreef and Breakwater sites under windward and leeward exposure conditions at T0, T12, and T24. Abundance is expressed as the number of individuals per 0.035 m².

Habitat	Exposure	Time	N	S	H'	J'
Breakwater	Leeward	T0	156.3 $\pm$ 8.7	11.0 $\pm$ 1.0	0.81 $\pm$ 0.08	0.34 $\pm$ 0.04
Breakwater	Leeward	T12	143.6 $\pm$ 14.7	10.6 $\pm$ 1.5	1.14 $\pm$ 0.06	0.48 $\pm$ 0.05
Breakwater	Leeward	T24	165.4 $\pm$ 12.5	17.0 $\pm$ 1.0	1.49 $\pm$ 0.12	0.53 $\pm$ 0.05
Breakwater	Windward	T0	58.1 $\pm$ 14.1	18.0 $\pm$ 0.2	1.89 $\pm$ 0.15	0.65 $\pm$ 0.05
Breakwater	Windward	T12	53.8 $\pm$ 12.7	17.6 $\pm$ 0.5	1.89 $\pm$ 0.19	0.66 $\pm$ 0.07
Breakwater	Windward	T24	87.4 $\pm$ 12.7	17.6 $\pm$ 0.5	2.49 $\pm$ 0.03	0.87 $\pm$ 0.02
Tecnoreef	Leeward	T0	53.1 $\pm$ 60.2	9.0 $\pm$ 1.0	1.25 $\pm$ 0.23	0.58 $\pm$ 0.13
Tecnoreef	Leeward	T12	58.3 $\pm$ 43.6	9.3 $\pm$ 0.5	1.80 $\pm$ 0.20	0.81 $\pm$ 0.10
Tecnoreef	Leeward	T24	184.1 $\pm$ 40.1	11.0 $\pm$ 1.7	1.50 $\pm$ 0.33	0.62 $\pm$ 0.11
Tecnoreef	Windward	T0	55.6 $\pm$ 13.4	18.0 $\pm$ 2.1	2.01 $\pm$ 0.18	0.69 $\pm$ 0.04
Tecnoreef	Windward	T12	33.2 $\pm$ 6.3	18.3 $\pm$ 2.5	2.28 $\pm$ 0.24	0.79 $\pm$ 0.06
Tecnoreef	Windward	T24	116.9 $\pm$ 23.2	17.8 $\pm$ 1.5	2.75 $\pm$ 0.19	0.95 $\pm$ 0.04

Note: Because statistical inference was based on a multifactorial ANOVA including interaction terms, alphabetical groupings from pairwise post hoc comparisons are not presented. See Supplementary Table S1 for the complete statistical results.

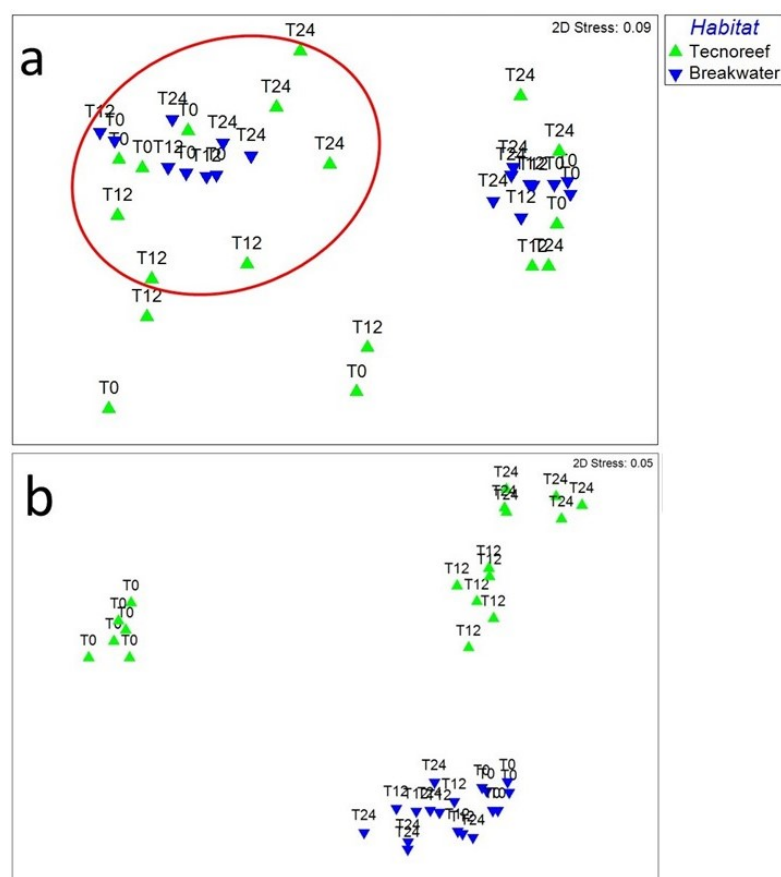


Figure 2. Non-metric multidimensional scaling (nMDS) ordinations based on Bray–Curtis similarities of abundance data at time T0, T12 and T24. (a) Infaunal assemblages; the red circle highlights samples collected at leeward stations. (b) Epifaunal assemblages. Distances among points reflect differences in community composition.

Permutational multivariate analysis of variance (PERMANOVA) identified hydrodynamic exposure as the main factor structuring infaunal assemblages, with significant differences between windward and leeward stations (Supplementary Materials, Table S2). Community composition also varied significantly over time, whereas no significant differences were detected between Tecnoreef and breakwater sites. None of the interaction terms were significant, indicating that the effects of exposure and time were consistent across habitat types (Supplementary Materials, Table S2).

SIMPER analysis (Table 2) identified the 14 taxa contributing most (cumulative contribution = 90.87%) to the dissimilarity between windward and leeward assemblages (average dissimilarity = 78.03%). *Lentidium mediterraneum* provided the highest contribution to the average Bray–Curtis dissimilarity between exposure (47.1%), followed by *Mactra stultorum* (12.77%), and *Tritia neritea* (6.79%). Together, these 3 taxa accounted for a substantial proportion (66.66%) of the observed differences in community composition between different exposure.

Table 2. SIMPER analysis identifying the taxa contributing most to the dissimilarity between windward and leeward infaunal assemblages. Reported values include average abundance (Avg N) in each exposure, percentage contribution to total dissimilarity (Contrib%), cumulative percentage contribution (Cum.%), and Feeding guild. Species are ordered by decreasing contribution to dissimilarity.

	Windward Leeward		Contrib%	Cum.%	Feeding Guild
	Avg N	Avg N			
<i>Lentidium mediterraneum</i> (O. G. Costa, 1830)	8.07	85.87	47.1	47.1	SF
<i>Mactra stultorum</i> (Linnaeus, 1758)	16.54	0.33	12.77	59.87	SF
<i>Tritia neritea</i> (Linnaeus, 1758)	11.21	2.88	6.79	66.66	Sc/Pr
<i>Ruditapes philippinarum</i> (A. Adams & Reeve, 1850)	1.96	9.0	5.17	71.83	SF
<i>Spio filicornis</i> (Müller, 1776)	1.48	5.33	3.02	74.85	DF
<i>Donax semistriatus</i> Poli, 1795	3.37	4.52	2.6	77.45	SF
<i>Capitella minima</i> Langerhans, 1880	1.36	3.61	2.45	79.91	DF
<i>Hediste diversicolor</i> (O.F. Müller, 1776)	3.06	1.0	1.98	81.89	Pr/Sc
<i>Chamelea gallina</i> (Linnaeus, 1758)	2.83	1.03	1.92	83.81	SF
<i>Spisula subtruncata</i> (da Costa, 1778)	2.24	1.47	1.55	85.36	SF
<i>Solen marginatus</i> Pulteney, 1799	2.28	1.47	1.54	86.89	SF
<i>Tritia nitida</i> (Jeffreys, 1867)	1.89	0.54	1.38	88.27	Sc/Pr
<i>Anadara inaequalis</i> (Bruguère, 1789)	1.62	1.29	1.33	89.6	SF
<i>Callinectes sapidus</i> Rathbun, 1896	1.32	1.06	1.27	90.87	Pr/Sc

Note: Feeding guilds: DF: deposit feeders; SF: suspension feeders; Pr: predators; Sc: scavengers.

The infaunal communities remained largely structured by local hydrodynamic conditions. Nevertheless, the increase in abundance and diversity observed around the submerged reefs suggests that the structures may have contributed to improving habitat suitability for soft-bottom benthic organisms, promoting the development of more mature assemblages in the surrounding sediments.

3.2. Epifaunal Communities

In total, 72 epifaunal taxa were documented on the submerged Tecnoreef modules throughout the study period, while the control breakwaters yielded 54 taxa. The assemblages were dominated by *Sabellaria spinulosa*, *Mytilus galloprovincialis*, *Polydora cornuta*, *Streblospio shrubsolei*, and *Monocorophium acherusicum*, which represented the most abundant taxa across all samples.

Univariate analyses revealed marked differences in the response of epifaunal community descriptors to habitat type, exposure, and time (mean $\pm$ SD values are reported

in Table 3, while full ANOVA results are provided in Supplementary Materials, Table S3). Total abundance (N) was significantly affected by all three factors and by all interaction terms, indicating that temporal changes in abundance differed between habitats and exposure conditions. The strongest effects were associated with habitat and time, reflecting substantial differences in colonization dynamics between Tecnoreef modules and breakwaters throughout the monitoring period. Species richness (S) was strongly influenced by habitat and time, whereas exposure had no significant effect. The highly significant habitat $\times$ time interaction indicates that species accumulation followed different trajectories on the two substrate types, with community development on Tecnoreef modules diverging from that observed on breakwaters. In contrast, Shannon diversity (H') and Pielou's evenness (J) were not significantly affected by habitat or exposure as individual factors. However, both indices showed significant habitat $\times$ time interactions, indicating that temporal changes in community structure differed between Tecnoreef modules and breakwaters. Time significantly affected evenness, whereas its effect on Shannon diversity was not significant.

Table 3. Mean ($\pm$ SD) values of total abundance (N), species richness (S), Shannon–Wiener diversity (H' , $\log_2$), and Pielou's evenness (J') for epifaunal assemblages sampled at Tecnoreef and Breakwater sites under windward and leeward exposure conditions at T0, T12, and T24. Abundance is expressed as number of individuals per 0.04 m².

Habitat	Exposure	Time	N	S	H'	J'
Breakwater	Leeward	T0	351.1 $\pm$ 22.8	44.3 $\pm$ 2.5	2.5 $\pm$ 0.1	0.69 $\pm$ 0.03
Breakwater	Leeward	T12	193.9 $\pm$ 41.9	34 $\pm$ 1.7	2.4 $\pm$ 0.03	0.68 $\pm$ 0.02
Breakwater	Leeward	T24	167.7 $\pm$ 22.1	39.3 $\pm$ 0.6	2.6 $\pm$ 0.1	0.69 $\pm$ 0.03
Breakwater	Windward	T0	344.2 $\pm$ 32.2	44 $\pm$ 3.5	2.6 $\pm$ 0.05	0.69 $\pm$ 0.03
Breakwater	Windward	T12	262.6 $\pm$ 24.9	34.6 $\pm$ 1.5	2.2 $\pm$ 0.2	0.63 $\pm$ 0.06
Breakwater	Windward	T24	238.2 $\pm$ 34.9	36.6 $\pm$ 2.1	2.4 $\pm$ 0.1	0.66 $\pm$ 0.02
Tecnoreef	Leeward	T0	71.2 $\pm$ 9.8	21.3 $\pm$ 0.6	2.3 $\pm$ 0.04	0.75 $\pm$ 0.01
Tecnoreef	Leeward	T12	404.8 $\pm$ 40.8	66 $\pm$ 1.7	2.8 $\pm$ 0.2	0.66 $\pm$ 0.04
Tecnoreef	Leeward	T24	1003 $\pm$ 51	67.3 $\pm$ 0.6	2.5 $\pm$ 0.1	0.58 $\pm$ 0.01
Tecnoreef	Windward	T0	73.3 $\pm$ 5.7	20.3 $\pm$ 2.1	2.3 $\pm$ 0.06	0.77 $\pm$ 0.05
Tecnoreef	Windward	T12	356.5 $\pm$ 41.9	62.6 $\pm$ 1.5	2.7 $\pm$ 0.05	0.66 $\pm$ 0.02
Tecnoreef	Windward	T24	614.7 $\pm$ 47.2	67.3 $\pm$ 0.6	2.5 $\pm$ 0.1	0.58 $\pm$ 0.03

Note: Because statistical inference was based on a multifactorial ANOVA including interaction terms, alphabetical groupings from pairwise post hoc comparisons are not presented. See Supplementary Table S3 for the complete statistical results.

The univariate analyses indicate that epifaunal succession was primarily driven by habitat type and time since deployment. While abundance and species richness responded strongly to the introduction of the Tecnoreef structures, changes in diversity and evenness were mainly associated with temporal shifts in community organization occurring on the two substrate types.

nMDS based on Bray–Curtis dissimilarities showed a clear separation of samples according to habitat type and sampling period (Figure 2b). Samples collected on Tecnoreef modules and breakwaters occupied distinct regions of the ordination space. The displacement of samples through time was pronounced for Tecnoreef assemblages, with samples collected at T0 separated from those collected at T12 and T24. In contrast, windward and leeward samples showed substantial overlap within the ordination space.

PERMANOVA identified habitat and time as the principal drivers of epifaunal community composition (Supplementary Materials, Table S4). Exposure did not significantly affect assemblage structure when considered independently. However, significant habitat $\times$ exposure and habitat $\times$ time interactions indicate that community development varied

between Tecnoreef modules and breakwaters and that the effects of hydrodynamic exposure differed according to substrate type. No significant exposure $\times$ time or three-way interactions were detected (Supplementary Materials, Table S4).

SIMPER analysis (Table 4) identified the 20 taxa contributing most (cumulative contribution = 90.09%) to the dissimilarity between Tecnoreef and breakwater assemblages (average dissimilarity = 70.13%). *Sabellaria spinulosa* provided the highest contribution to the average Bray–Curtis dissimilarity between habitats (21.31%), followed by *Mytilus galloprovincialis* (16.15%), *Melita palmata* (8.22%), *Polydora cornuta* (7.14%), and *Cirratulus cirratus* (5.9%). Together, these 5 taxa accounted for a substantial proportion (58.73%) of the observed differences in community composition between the two substrate types.

Table 4. SIMPER analysis identifying the taxa contributing most to the dissimilarity between Tecnoreef and breakwater epifaunal assemblages. Reported values include average abundance (Avg N) in each habitat, percentage contribution to total dissimilarity (Contrib%), and cumulative percentage contribution (Cum.%), and Feeding guild. Species are ordered by decreasing contribution to dissimilarity.

	Tecnoreef	Breakwater			Feeding Guild
	Avg N	Avg N	Contrib%	Cum.%	
<i>Sabellaria spinulosa</i> Leuckart, 1849	134.49	3.84	21.31	21.31	SF
<i>Mytilus galloprovincialis</i> Lamarck, 1819	34.5	82.33	16.15	37.46	SF
<i>Melita palmata</i> (Montagu, 1804)	2.66	33.2	8.22	45.68	Om/DF
<i>Polydora cornuta</i> Bosc, 1802	55.38	5.87	7.14	52.83	DF
<i>Cirratulus cirratus</i> (O. F. Müller, 1776)	0.08	21.83	5.9	58.73	DF
<i>Streblospio shrubsolii</i> (Buchanan, 1890)	30.11	12.38	4.96	63.69	DF
<i>Monocorophium acherusicum</i> (A. Costa, 1853)	25.11	15.76	4.51	68.2	DF
<i>Hydroides dianthus</i> (Verrill, 1873)	18.07	6.23	3.11	71.31	SF
<i>Amphibalanus improvisus</i> Darwin, 1854	5.14	14.04	3.05	74.36	SF
<i>Arcuatula senhousia</i> (Benson in Cantor, 1842)	2.98	9.0	1.98	76.34	SF
<i>Monocorophium insidiosum</i> (Crawford, 1937)	6.67	9.39	1.83	78.17	DF
<i>Syllis gracilis</i> Grube, 1840	11.12	3.13	1.63	79.8	Pr/Om
<i>Caprella scaura</i> Templeton, 1836	7.58	6.91	1.56	81.36	Om/Gr
<i>Aiptasiogeton pellucidus</i> (Holland, 1848)	9.22	1.29	1.55	82.9	Pr
<i>Armandia cirrhosa</i> Filippi, 1861	6.04	2.33	1.54	84.45	DF
<i>Amphibalanus eburneus</i> Gould, 1841	2.46	5.81	1.29	85.74	SF
<i>Tanais dulongii</i> (Audouin, 1826)	7.63	0.89	1.27	87.01	DF/Gr
<i>Hydroides elegans</i> (Haswell, 1883)	5.19	0.98	1.13	88.14	SF
<i>Pomatoceros triqueter</i> (Linnaeus, 1767)	6.39	4.99	1.01	89.15	SF
<i>Alitta succinea</i> (Leuckart, 1847)	3.12	2.8	0.94	90.09	Pr/Om

Note: Feeding guilds: DF: deposit feeders; SF: suspension feeders; Gr: grazers; Pr: predators; Om: omnivores.

Epifaunal assemblages differed significantly between Tecnoreef modules and breakwaters and exhibited significant temporal variation during the monitoring period, while no significant main effect of exposure was detected.

4. Discussion

4.1. Effects of Submerged Reefs on Soft-Bottom Infaunal Communities

The deployment of submerged restoration structures did not result in the establishment of a distinct infaunal assemblage in the surrounding sediments. Community composition remained broadly similar between submerged reefs and control breakwaters, while hydrodynamic exposure emerged as the primary factor structuring benthic assemblages. This result is consistent with the highly dynamic sedimentary environments of the northern

Adriatic Sea, where sediment transport and small-scale hydrodynamic variability strongly influence benthic communities [22].

Nevertheless, the absence of significant compositional differences does not imply a lack of restoration effect. Although the reefs did not alter the taxonomic identity of the infaunal assemblage, they were associated with increased abundance and diversity throughout the monitoring period, suggesting improved habitat suitability for existing soft-bottom species rather than the establishment of a novel community.

From a restoration perspective, these findings are particularly relevant, as contemporary restoration increasingly focuses on enhancing ecosystem functioning and resilience rather than creating entirely new communities [23]. The observed increases in abundance and diversity may reflect improved local conditions, including reduced sediment disturbance, enhanced food availability, greater organic matter retention, or the formation of localized hydrodynamic refuges around the reef modules. Similar indirect effects on adjacent soft-bottom habitats have been reported for artificial reefs and other habitat-enhancement structures [24].

Our results suggest that submerged restoration structures can enhance the ecological quality of soft-bottom habitats without inducing major shifts in community composition. Rather than driving community replacement, the reefs appear to facilitate ecological maturation, supporting more abundant and diverse assemblages of native benthic species.

4.2. Epifaunal Community Development and the Emergence of *Sabellaria spinulosa* Bioconstructions

The rapid development of epifaunal assemblages on the Tecnoreef modules (Figure 3) was accompanied by the progressive growth of *Sabellaria spinulosa* bioconstructions. After only two years, all Tecnoreef plates included in the biological monitoring were completely covered by *S. spinulosa* bioconstructions. On these monitored plates, the biogenic matrix reached thicknesses exceeding 10 cm, indicating rapid three-dimensional habitat development and a substantial increase in habitat complexity. However, the present monitoring programme was designed to assess benthic community development rather than to perform a comprehensive morphometric survey of the entire restoration system, which comprises more than 1000 deployed plates. Consequently, quantitative estimates of the total spatial extent and volumetric development of *S. spinulosa* bioconstructions across the full installation were beyond the scope of the present study. The epifaunal assemblages differed significantly from those associated with the adjacent limestone breakwaters, highlighting the importance of substrate architecture in shaping colonization patterns. While artificial hard substrates commonly support diverse fouling communities [11], the most notable result was the progressive establishment of *S. spinulosa*, one of the taxa contributing most strongly to the differentiation between Tecnoreef and breakwater assemblages.

The ecological significance of this finding extends beyond simple species occurrence. *S. spinulosa* is a reef-building polychaete and a recognized ecosystem engineer capable of generating complex biogenic structures through the aggregation of thousands of sand-cemented tubes [25,26]. These bioconstructions increase habitat heterogeneity, provide refuge and nursery grounds for numerous species, and contribute to ecosystem functioning [27–29]. Consequently, the colonization of the Tecnoreef modules by *S. spinulosa* represents a process qualitatively different from typical artificial reef colonization, as the engineered substrate becomes the foundation for the development of a secondary biogenic habitat. Beyond its numerical dominance, *S. spinulosa* represents one of the clearest indicators of habitat transformation observed in this study. Its major contribution to the dissimilarity between Tecnoreef and breakwater assemblages reflects the progressive shift from exposed concrete surfaces to a structurally complex biogenic habitat generated through biological construction.

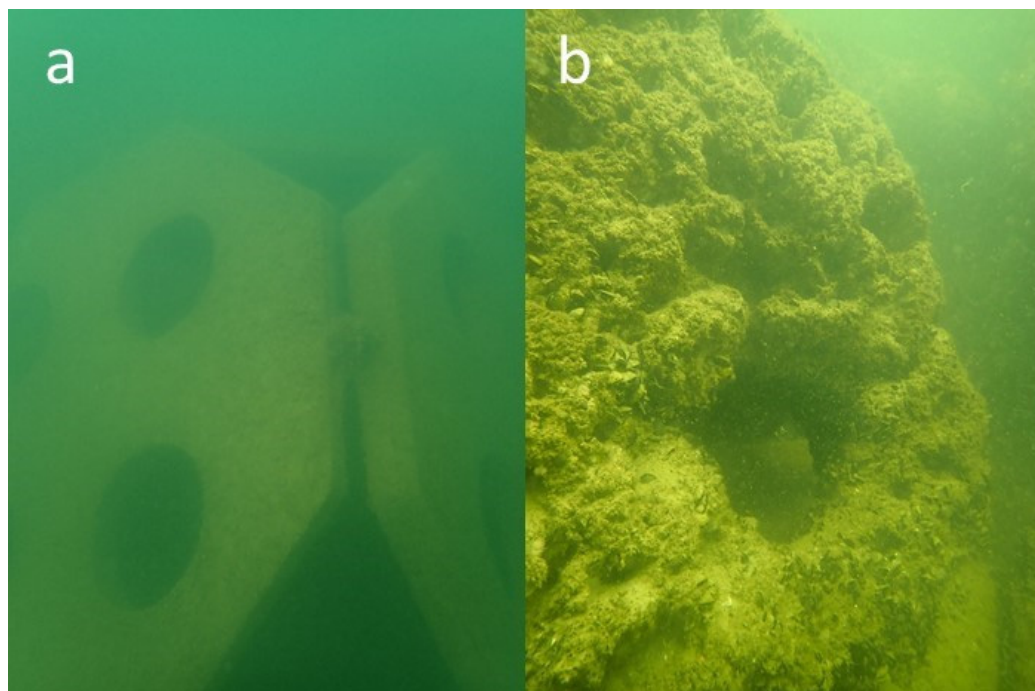


Figure 3. Temporal development of the epifaunal cover on the Tecnoreef modules: (a) July 2021 (T0), few weeks after deployment; (b) July 2023 (T24), showing a mature organogenic cover and well-developed bioconstructions on the module surface. At this stage, the original concrete plates are almost completely obscured by biological growth and are distinguishable only by the presence of the characteristic perforations in the module structure.

While the rapid transition from bare concrete to a biogenic habitat represents a key milestone for coastal eco-engineering, this short-term pattern must be evaluated against broader environmental and biological forcing factors. First, the local hydrology of the northern Adriatic coastal strip is strongly influenced by episodic riverine discharges (e.g., the Po River plume), which introduce sharp gradients in salinity, nutrient concentrations, and suspended particulate matter. These fluctuations directly dictate the trophic resources available to dominant suspension feeders (*S. spinulosa* and *M. galloprovincialis*), meaning that years with contrasting river flow could yield different colonization densities. Second, intense climatic seasonality, characterized by extreme winter hydrodynamics (storm surges capable of mechanically eroding sandy tubes) and severe summer sea-surface temperature anomalies (which can trigger localized hypoxia or physiological stress), introduces interannual instability that a two-year dataset cannot fully integrate. Finally, the natural processes of ecological succession are still unfolding. The current community reflects an intermediate successional stage where space competition between the bioconstructors (*S. spinulosa* and *M. galloprovincialis*) and opportunistic epibionts (e.g., *Polydora cornuta*) is highly dynamic. Long-term monitoring is therefore crucial to determine if these biogenic structures will maintain their structural integrity or adapt through cyclical successional shifts under changing climatic and hydrological regimes.

The rapid dominance of *S. spinulosa* observed in this study highlights its specific role as a primary ecosystem engineer in the shallow, sediment-rich environments of the northern Adriatic. However, globally, the identity of the pioneering species that initiates hard-substrate colonization varies widely. While in Western Europe sabellarids (*S. spinulosa* and *S. alveolata*) frequently act as early colonizers due to their affinity for turbulent, sand-saturated waters [30], other regions exhibit different successional pathways. For instance, along the subtropical Western Atlantic, the reef-building polychaete *Phragmatopoma caudata* initiates similar biogenic frameworks [31]. Conversely, in many temperate coastal systems,

the earliest colonization phases are driven by opportunistic hydrozoans, bryozoans [32], or serpulid polychaetes like *Ficopomatus enigmaticus* [33], or by fast-growing bivalves [34] that bypass the polychaete phase entirely. Acknowledging these diverse regional pathways underscores that, while our modular reef success denotes a localized structural regeneration led by *S. spinulosa*, eco-engineering outcomes are strictly bound to regional larval pools and biogeographical traits.

Although *S. spinulosa* is widespread in European waters [35], well-developed bioconstructions remain relatively uncommon in the Adriatic Sea. The first detailed descriptions of extensive Adriatic reefs were reported from the Apulian coast at Torre Mileto, where bioconstructions extending over approximately 10,000 m² were documented [26,36]. These reefs undergo alternating phases of growth and degradation but nevertheless support highly diverse benthic assemblages and function as biodiversity hotspots [26]. More recently, previously undocumented *S. spinulosa* biogenic reefs have been identified along the Emilia–Romagna coast, suggesting that suitable environmental conditions for their development may be more widespread in the northern Adriatic than previously recognized [37].

The origin of the *S. spinulosa* propagules colonizing the Tecnoreef modules cannot be determined directly from the present study. However, the species was already present on the adjacent breakwaters, albeit at considerably lower abundance and without developing comparable bioconstructions. This observation suggests that local propagule sources were already available within the study area and that larval supply was unlikely to represent the primary limitation to colonization.

The markedly different development of *S. spinulosa* on Tecnoreef modules compared with nearby breakwaters points to differences in habitat suitability rather than propagule availability. While the breakwaters consist of relatively compact limestone boulders with limited internal complexity, the Tecnoreef modules provide a highly porous three-dimensional architecture characterized by cavities, crevices, sheltered surfaces, and numerous attachment points. Such features may enhance larval retention, settlement success, and post-settlement survival, while also creating favorable hydro-dynamic conditions for suspension-feeding organisms. The rapid expansion of *S. spinulosa* observed on the Tecnoreef modules therefore likely reflects the interaction between local larval availability and the provision of environmental conditions conducive to bioconstruction development. These observations suggest that structurally complex artificial substrates can facilitate the local expression of ecological processes already present within the regional species pool but only weakly manifested on conventional coastal defense structures.

The ecological implications of this process are particularly relevant from a restoration perspective. Mature *S. spinulosa* reefs support diverse assemblages of polychaetes, crustaceans, molluscs, echinoderms, and numerous vagile species that utilize the reef matrix as shelter and feeding grounds [26]. Similar positive feedback mechanisms have been described for other ecosystem-engineering habitats, including mussel beds, oyster reefs, and coralligenous formations [25,38]. Rather than functioning solely as artificial habitats, the Tecnoreef modules may have acted as ecological facilitators, promoting the establishment of a habitat-forming species capable of generating additional structural complexity through natural processes.

Our results suggest that the ecological role of the Tecnoreef modules extends beyond the provision of artificial hard substrate. By facilitating the establishment of *S. spinulosa*, the structures initiated the development of a secondary biogenic habitat that may contribute to increased biodiversity and habitat heterogeneity over longer time-scales. Although the monitoring period was insufficient to assess habitat persistence, resilience, or ecosystem functioning, the observed colonization patterns provide encouraging evidence of ecological trajectories consistent with habitat development in a highly modified coastal environment.

Given the conservation importance of sabellariid habitats in European waters [30], these findings highlight the potential of eco-engineered reefs as nature-based tools for supporting biodiversity enhancement and habitat development in sedimentary coastal ecosystems.

4.3. Eco-Engineering with Tecnoreef Modules: Economic Viability and Ecological Succession

From an engineering perspective, deploying eco-engineered solutions like the Tecnoreef modules involves distinct economic considerations. While the specialized fabrication of eco-compatible concrete structures entails higher upfront production costs compared to traditional quarry stone dumping, these are often balanced by optimized logistics. The lightweight, modular nature of the blocks simplifies maritime deployment, allowing the use of smaller vessels (Figure 1d) and reducing local site disruption. From an ecological standpoint, it must be emphasized that the 2-year timeframe of this study represents a snapshot of early-to-intermediate succession. In the northern Adriatic Sea, macrobenthic communities on artificial hard substrates generally require a minimum of 3 to 5 years to complete pioneering colonization sequences and transition into mature, structurally stable climax communities [1,14]. Consequently, the high densities of *S. spinulosa* and *M. galloprovincialis* observed in year two should be viewed as a highly positive trajectory toward maturity, rather than a final stabilized ecosystem state.

4.4. Study Limitations and Future Research Directions

The present study has some limitations that should be considered when interpreting the results. First, no direct measurements of environmental variables such as current velocity, wave exposure, sediment grain size, or organic matter content were collected at the sampling stations during the monitoring period. Although environmental information for the study area is available through the ARPAE Emilia–Romagna monitoring network (<https://www.arpae.it/it/temi-ambientali/mare/dati-e-indicatori/mappa-dati-mare> accessed on 10 May 2026), these datasets were not collected concurrently with the biological surveys. Consequently, our interpretation of the mechanisms underlying the observed community patterns should be regarded as hypothesis-driven rather than directly demonstrated. Future studies combining biological monitoring with concurrent measurements of hydrodynamics, sediment characteristics, and organic matter will allow a more mechanistic understanding of the ecological processes governing habitat development around eco-engineered reefs.

Second, the assessment focused primarily on taxonomic responses, including community composition, abundance, richness, diversity, and evenness. Although these metrics provide valuable information on ecological change, they do not directly address functional aspects of ecosystem recovery. The incorporation of functional indicators, such as trophic structure, biological trait analyses, or functional diversity metrics, would provide a more comprehensive understanding of how eco-engineered reefs influence ecosystem functioning and resilience. Nevertheless, the marked development of *Sabellaria spinulosa* bioconstructions and dense aggregations of *Mytilus galloprovincialis* suggests that the epifaunal assemblages developing on the Tecnoreef modules were increasingly dominated by suspension-feeding organisms, potentially indicating important shifts in trophic structure and benthic–pelagic coupling processes. Quantifying these functional changes represents an important priority for future research.

Finally, a limitation concerns its spatial replication, which was conducted within a single coastal restoration project across eco-engineered reef installations and adjacent conventional breakwaters. While this setup is common in artificial reef assessments where designs are inherently constrained by the number of available structures [13,14,17], it limits the ability to account for small-scale spatial heterogeneity. Consequently, caution is required when extrapolating these ecological responses beyond the study area. Future research

incorporating multiple restoration sites across broader environmental gradients would improve the generality of these findings, helping to isolate treatment effects from natural spatial variability and robustly assess the consistency of eco-engineered reef performance.

5. Conclusions

This study provides one of the first evaluations of eco-engineered submerged reefs deployed within a tourism-dominated sandy shoreline of the northern Adriatic Sea. The results indicate that benthic communities responded differently to the introduction of the restoration structures, with contrasting patterns observed between soft-bottom and hard-substrate assemblages.

The submerged reefs had limited effects on the overall composition of surrounding infaunal communities, which remained primarily structured by hydrodynamic conditions. Nevertheless, increases in abundance and diversity around the structures suggest that the reefs may have improved habitat suitability for existing soft-bottom species. In contrast, epifaunal assemblages exhibited pronounced temporal changes and developed community compositions distinct from those observed on adjacent breakwaters, indicating that substrate architecture and structural complexity strongly influenced colonization processes.

The introduction of the Tecnoreef modules increased habitat heterogeneity within an otherwise homogeneous sedimentary environment and was associated with the development of diverse epifaunal assemblages. Particularly noteworthy was the progressive colonization of the structures by the reef-building polychaete *Sabellaria spinulosa*, a recognized ecosystem engineer and habitat-forming species of conservation interest in European waters. After only two years, *S. spinulosa* had developed conspicuous bioconstructions on portions of the modules, suggesting that the artificial structures provided suitable conditions for the early stages of biogenic habitat development.

Although the monitoring period does not allow conclusions regarding long-term ecosystem recovery, resilience, or ecosystem functioning, the observed patterns provide encouraging evidence of ecological trajectories consistent with habitat development and biodiversity enhancement. The establishment of *S. spinulosa* and the progressive increase in epifaunal complexity indicate that eco-engineered submerged reefs can initiate ecological trajectories conducive to the development of structurally complex benthic assemblages. However, the present two-year monitoring period documents only the early stages of colonization and habitat development, and does not allow assessment of the long-term stability, persistence, or resilience of these emerging biogenic communities. Future monitoring should include standardized morphometric surveys to quantify the spatial coverage, thickness, and volumetric development of *S. spinulosa* bioconstructions across a representative subset of the deployed modules, thereby allowing assessment of reef expansion at the installation scale.

Longer-term monitoring will be required to assess the persistence, spatial extent, and structural development of the observed bioconstructions, as well as their contribution to ecosystem functioning and biodiversity conservation. Nevertheless, the present study suggests that eco-engineered submerged reefs may represent a promising nature-based solution for increasing habitat complexity and supporting biodiversity in anthropogenically modified coastal systems. In particular, their ability to facilitate the establishment of habitat-forming species highlights their potential relevance for future coastal restoration initiatives aligned with the objectives of the EU Nature Restoration Regulation and the UN Decade on Ecosystem Restoration. Continued long-term monitoring will be essential to determine whether the observed colonization trajectories lead to self-sustaining and stable benthic ecosystems over ecologically relevant timescales.

Several limitations should be considered when interpreting these findings. First, the two-year monitoring period captures only early ecological succession rather than long-term ecosystem development. Second, environmental variables (e.g., hydrodynamics, sediment characteristics, and organic matter) were not measured concurrently, limiting direct inference on the physical mechanisms driving community patterns. Finally, spatial replication was constrained by the engineering design of a single restoration project. Future research should combine long-term biological monitoring with quantitative environmental metrics and expanded spatial replication across multiple sites. Additionally, incorporating standardized morphometric surveys of *S. spinulosa* bioconstructions would provide deeper insight into the long-term structural development, persistence, and functioning of these emerging biogenic habitats.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w18141673/s1>, Table S1: three-way ANOVAs on infaunal descriptors; Table S2: three-factor PERMANOVA on infaunal abundance; Table S3: three-way ANOVAs on epifaunal descriptors; Table S4: three-factor PERMANOVA on epifaunal abundance.

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