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Early benthic succession and pioneer community dynamics on 3D printed substrates at Koh Samaesan, Chon Buri Province

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Abstract. As coral reefs in many areas are degraded, various techniques for coral reef restoration have been developed. One popular method is the creation of artificial reefs, which are widely accepted for restoring habitats for coral reef communities. At present, 3D printing technology is used as a substrate for coral recruitment and is hoped to be one of the factors that help to further increase coral reef areas. This study aimed to examine the composition of benthic communities on the surface of 3D-printed. Data were collected six times during November 2024–September 2025 at Koh Samaesan, using a 15 × 15 cm quadrat sampling method, with quadrats randomly placed on the outer surfaces of the structures. Photos were taken in 6 quadrats per structure, with 15 replicates. A total of 10 categories of sessile benthic organisms were found. Marine sponge is the dominant benthic organisms on 3D-printed (4.14%), followed by turf algae (3.48%) and Mollusk (2.23), while 87.50% had no organisms attached to the structure. In terms of coral cover, which is the main purpose of the 3D-printed, only 0.10%, with two species are *Porites* sp., and *Oulastrea crispata*. Despite the results showing that 3D structures may not be optimal for the settlement of coral recruits, this study was conducted only six times over one year. Therefore, studies should be conducted continuously over 3–5 years to monitor and assess coral recruit settlement, including other functions of 3D-printed structures for the environment.

Keywords: coral reef restoration, 3D printing cement, artificial reef, coral, marine organism

1. Introduction

The coral reefs play a critical role in marine ecosystems by providing habitat and nursery grounds for a wide range of marine organisms (Stier et al. 2025). They also support tourism and contribute significantly to local economies (Spalding et al. 2017; Wallmo & Allen 2024). However, rising global temperatures of 1–2°C have led to widespread coral bleaching and a

significant decline in live coral cover worldwide (Hoegh-Guldberg 1999). In addition to climate related stressors, anthropogenic activities, particularly coastal development, have increased environmental pressures on coral reef systems. Sedimentation from coastal constructions. According from Stender et al. (2014), were studied coastal construction and increased sedimentation was related with coral reef change and affect coral health and lead to reef degradation. Due to the decline of coral reefs, scientists worldwide are researching and exploring ways to restore coral reef ecosystems. A hypothesis suggests increasing the surface area for coral recruitment to settle, and to test this hypothesis, materials have been developed that act as substrates in marine environments, allowing early colonizers to establish and grow, eventually forming a new ecosystem (Fujiwara et al. 2025; Yus et al. 2024; Reichert et al. 2025). Apart from their contributions to restoration and habitat creation, that demonstrate their potential as habitats for a diverse range of marine species, including both juveniles and adults (Becker et al. 2017).

In Thailand, artificial coral settlement substrate is a result of studies on benthic organisms colonizing artificial reefs, which were originally deployed to enhance marine habitats and fisheries resources (Phongsuwan et al. 1994; Kamthong et al. 2012; Rungruangthongthavee et al. 2014). Subsequently, the Faculty of Veterinary Medicine, Chulalongkorn University, collaborated with SCG Cement Public Company Limited and the Department of Marine and Coastal Resources, Ministry of Natural Resources and

Environment, to develop advanced materials using 3D printing technology for use as a substrate for coral larvae settlement, and these have been deployed in several areas (Figure 1), one of which is Koh Samaesan. Koh Samaesan is taken care of by the Royal Thai Navy and is an area in the Plant Genetic Conservation Project initiated by Her Royal Highness Princess Maha Chakri Sirindhorn, thus making it an excellent representative for studies in protected areas. This study aimed to examine early benthic succession and pioneer community dynamics on the surface of 3D-printed structures, and to use the data as a baseline for improving and developing artificial substrates in future ecological applications.

2. Materials and Methods

2.1 Study site

The colonization and ecological succession of benthic communities on 3D printed structures

was studied in the eastern part of Koh Samaesan at a depth of approximately 12 meters below mean sea level, next to the fish dome artificial reefs. A total of 64 units were deployed in April 2024, and they are arranged in a 5×8 grid, separated into 31 groups, each group arranging the structure in a different pattern to increase the diversity and complexity of the structure, making it more similar to coral reefs (Figure 2)

2.2 Data analysis

The data of benthic communities on 3D printed were first collected 9 months after deployment. The monitoring was then carried out continuously for one year, with surveys conducted every two months, total of six times between November 2024 and September 2025. The sampling was carried out on the same structure, with 15 groups, using a photoquadrat method adopted from Preskitt et al. (2004), a 15×15 cm quadrat with quadrats randomly placed on the outer surfaces of the structures (Figure 3).



Figure 1 3D-printed structures were deployed underwater

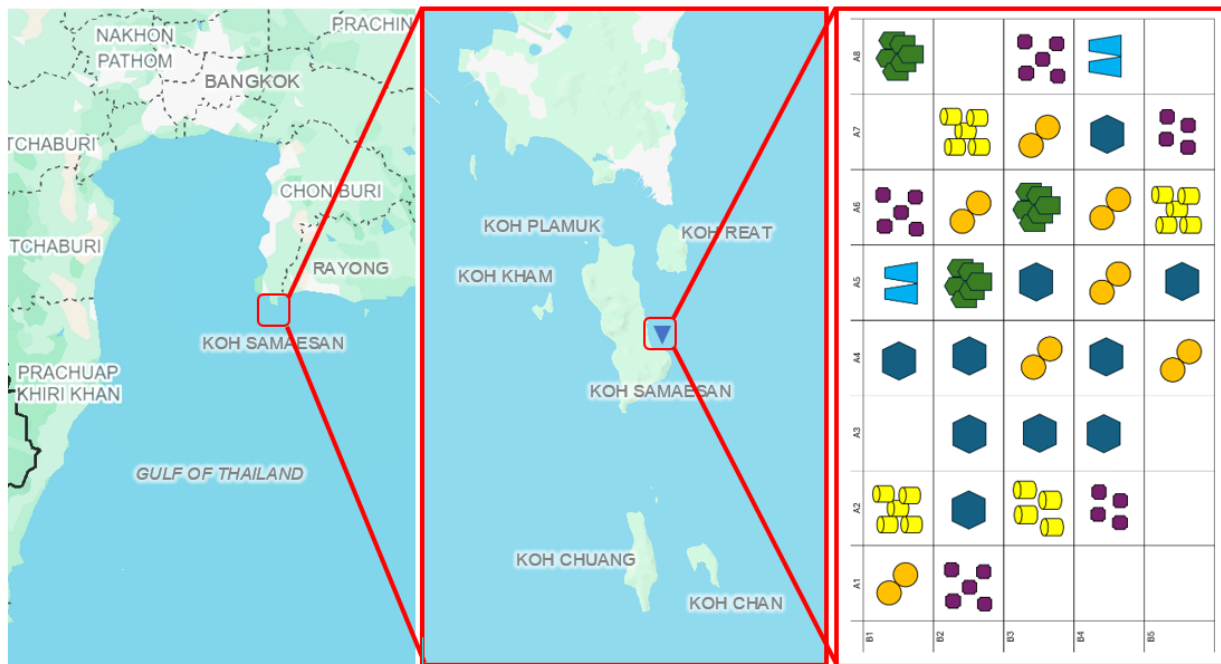


Figure 2 Study site of composition of benthic communities on 3D-printed structures

Photos were taken in 6 quadrats per group, and all images were classified and categorized into benthic groups: bryozoans, coralline algae, cyanobacteria, macroalgae, hydrozoans, hard coral, soft coral, sponges, ascidians, turf algae, zoanthid, gorgonia, and sediment with bare concrete, adopted from Hylkema et al. (2023) by the program Coral Point Count with Excel extensions (CPCe) (Kohler & Gill 2006). The program was set up by specifying stratified points assigned to five random rows and columns, with 25 points in each image. No analysis of quadrat orientation because the structures were relatively small with limited top-facing surfaces. In addition, the 3D-printed structures had varying shapes, so data collection was performed only on the lateral (side) surfaces. This represents a method limitation of the study.

2.3 Statistical analysis

The temporal trends in benthic communities were assessed using linear regression, revealing the direction and magnitude of change over time. Subsequently, Spearman correlation analysis was conducted to examine relationships among species, providing insights into potential ecological interactions, and the Friedman test

was used to assess differences in values over time (Friedman 1937). The results of spatial change of benthic communities were shown using heatmaps, Spearman correlation, linear regression, PERMANOVA (Anderson, 2017), and Principal Component Analysis (PCA) (Venables & Ripley 2002) to examine the changing trends of living things found on 3D structures. All statistical analyses were performed using R software (R Core Team 2025) in RStudio (Posit Team 2024). Data manipulation and visualization were conducted using the tidyverse packages (Wickham et al. 2019), corrplot (Kolde 2019), including dplyr and tidyr (Wickham 2024; Kuhn & Silge 2023). Graphs were produced using ggplot2 (Wickham 2016).

3. Results and Discussion

From the six data collections conducted over six periods from November 2024 to September 2025, 10 categories of sessile benthic organisms were identified, with sponges being the dominant benthic organisms on 3D-printed structures (4.14%), followed by algae (3.48%) and mollusks (2.23%), while 87.91% had no organisms attached to the structure (Table 1).

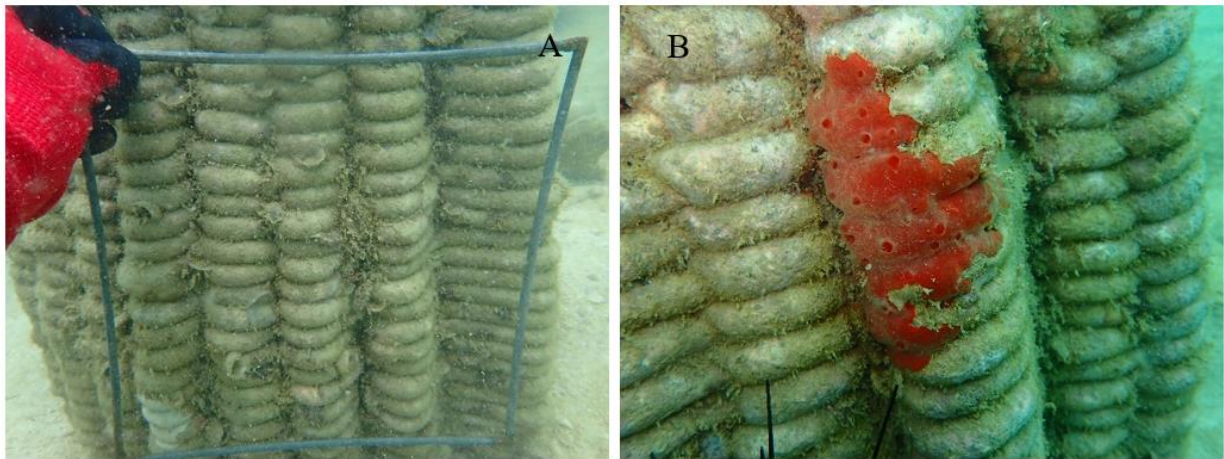


Figure 3 A photo quadrat method (A), and marine benthic on 3D-structure surface (B)

Table 1. An area cover (%) of sessile benthic organisms on 3D-structures

Categories/Times	An area cover (%)						Average area cover
	Nov 24	Jan 25	Mar 25	May 25	Jul 25	Sep 25	
Turf algae	1.98	2.38	4.98	3.79	2.08	5.65	3.48
Barnacle	1.01	2.38	0.67	1.54	0.92	0.44	1.16
Gorgonian	0.00	0.00	0.00	0.00	0.08	0.09	0.03
Hydroid	0.00	0.17	1.51	0.04	0.04	0.00	0.29
Mollusk (bivalve)	1.74	4.33	2.00	2.79	2.33	0.16	2.23
Sea cucumber	0.00	0.26	0.31	0.17	1.50	1.17	0.57
Sponges	0.73	2.03	5.29	5.08	5.79	5.90	4.14
Ascidians	0.08	0.00	0.00	0.00	0.17	0.38	0.11
Corals	0.00	0.04	0.09	0.21	0.12	0.16	0.10
Sediment with bare concrete	94.47	88.40	85.15	86.39	86.97	86.05	87.91
Total benthic cover	5.54	11.59	14.85	13.62	13.03	13.95	
Shannon-Wiener Index	1.37	1.34	1.49	1.43	1.55	1.28	

The results show the structure and changes of sessile benthic communities on 3D-printed structures. In detail, the spatial changes and colonization of benthic communities found on the structure are still in the early succession phase. This is because a large proportion of the area still consists of sediment with bare concrete, indicating that the sessile benthic communities may not be fully developed yet.

However, the dominant group found in the early stages of settlement was turf algae, which exhibited cyclical increases and decreases but maintained a consistent role throughout the study. This pattern reflects the ecological role of turf algae as pioneer colonizers with high settlement rates on newly available substrates.

Furthermore, turf algae have the capacity to quickly retain sediment and cover surfaces, leading to early spatial dominance and potentially hindering the settlement of other organisms (Fricke et al. 2011), such as corals, especially branching corals, which generally lose in competition with turf algae (Swierts & Vermeij 2016). To examine the settlement trends of sessile organisms found on structures, regression analysis was used to investigate the trends in changes of sessile organisms over time. The results, regression model showed 4 benthic organisms has positive significant statistic; corals, gorgonian, sponges, and sea cucumber in Synaptidae family (Table 2), that mean when time increase, corals, gorgonian, sponges, and sea cucumber were increase

(Figure 4). In term of interactive relationship between all benthic organism, correlations analysis showed a strong positive correlation with sponge and sea cucumber, gorgonian with sea cucumber and ascidians (Figure 5), especially sea cucumber in Synaptidae and sponge (Figure 6).

A strong positive correlation has been found between Synaptidae and sponge cover, resulting from these organisms using sponge surfaces as both a habitat (commensalism) and a food source (Mucharin et al. 2019), as Synaptidae feed on detritus, as well as bacteria and microalgae (Pierrat et al. 2022). Similarly, a strong positive correlation has been observed between Synaptidae and ascidians cover. Although there are no definitive reports on this relationship, field observations frequently show Synaptidae on ascidians, which contain large amounts of detritus (Figure 5). Despite significant regression and correlation results, the Friedman test (Chi-square = 5.7784, df = 5,

$p = 0.3284$) and heatmap indicated that benthic organisms remained at generally low levels throughout the study. Sponges and turf algae were the earliest colonizers and showed increasing trends. Other invertebrates increased slightly, while mollusks and hydroids displayed seasonal or episodic fluctuations. In contrast, corals remained at very low cover throughout the study (Figure 7).

This may be due to the layered structure, which acts as a sediment trap, inhibiting coral larval settlement and growth. PERMANOVA analysis found no significant differences between time periods due to sample size limitations, but trends from PCA show changes in pioneer communities over time (Figure 8), that showed surfaces were mostly bare sediment with a few pioneers like barnacles and bivalves in early, then, sponges, turf algae and other to expanded, covering surfaces and enabling more colonization a shift from bare substrate to a diverse benthic community over time.

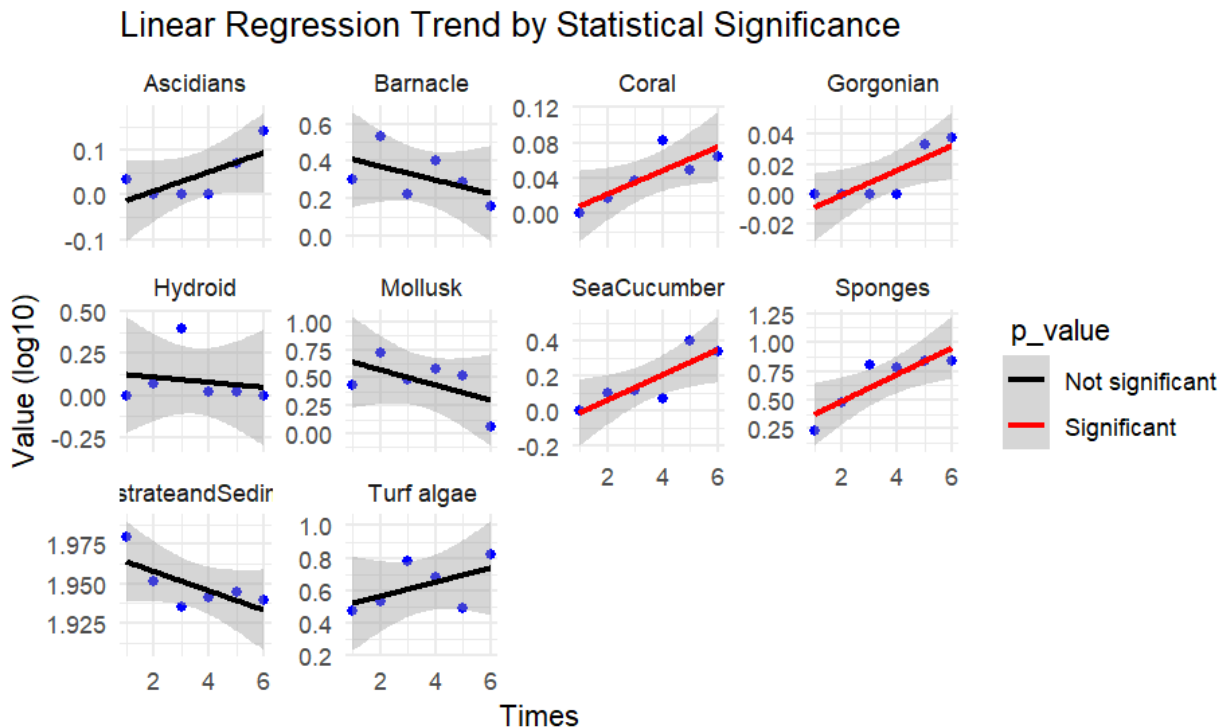


Figure 4 Linear regression analysis of each sessile benthic organisms across six times

Spearman Correlation Heatmap of Species

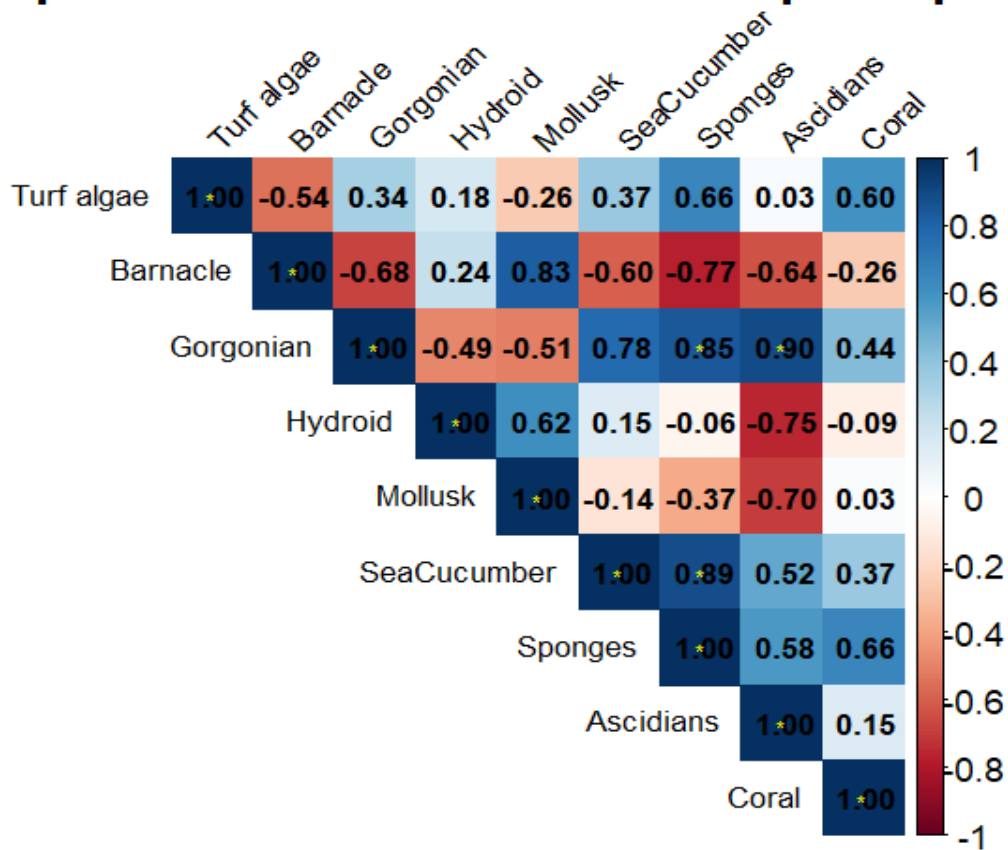


Figure 5 The spearman correlation heatmap for interactive relationship between all benthic organism

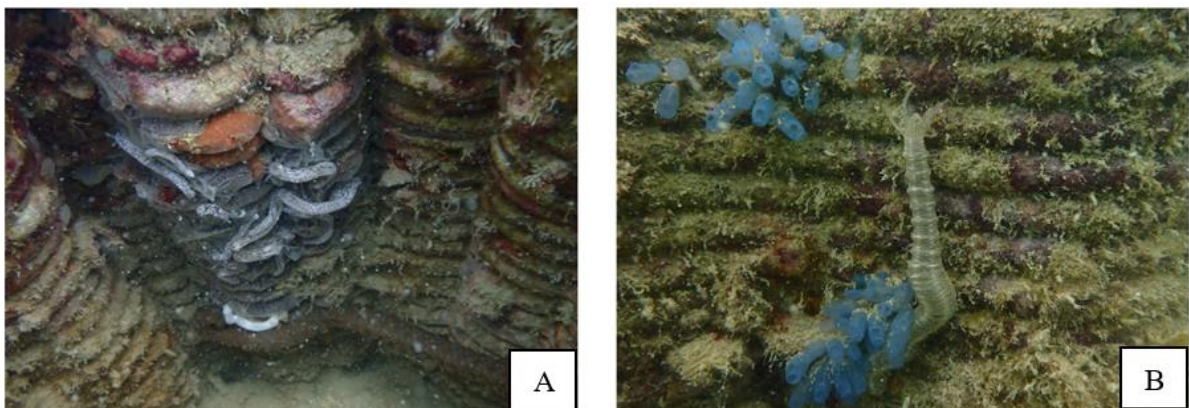


Figure 6 Synaptidae and sponge (A), and Synaptidae and ascidians (B) in filed survey

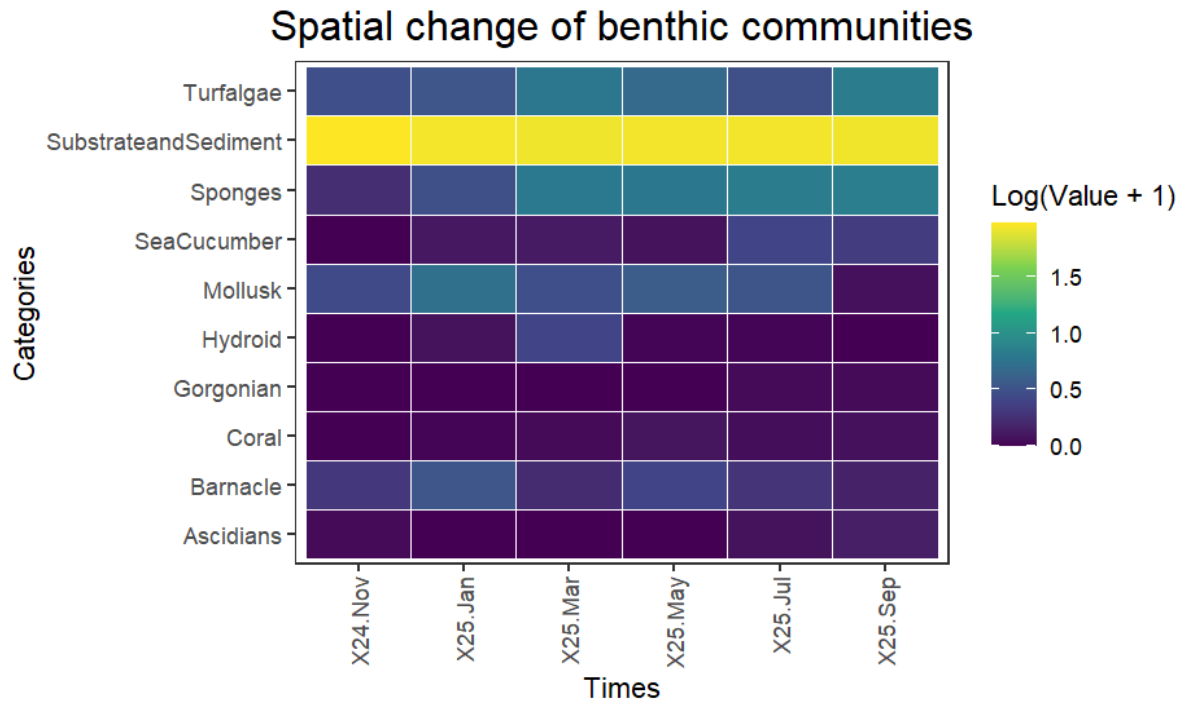


Figure 7 Heatmap show the spatial change of benthic community on 3D-printed structures

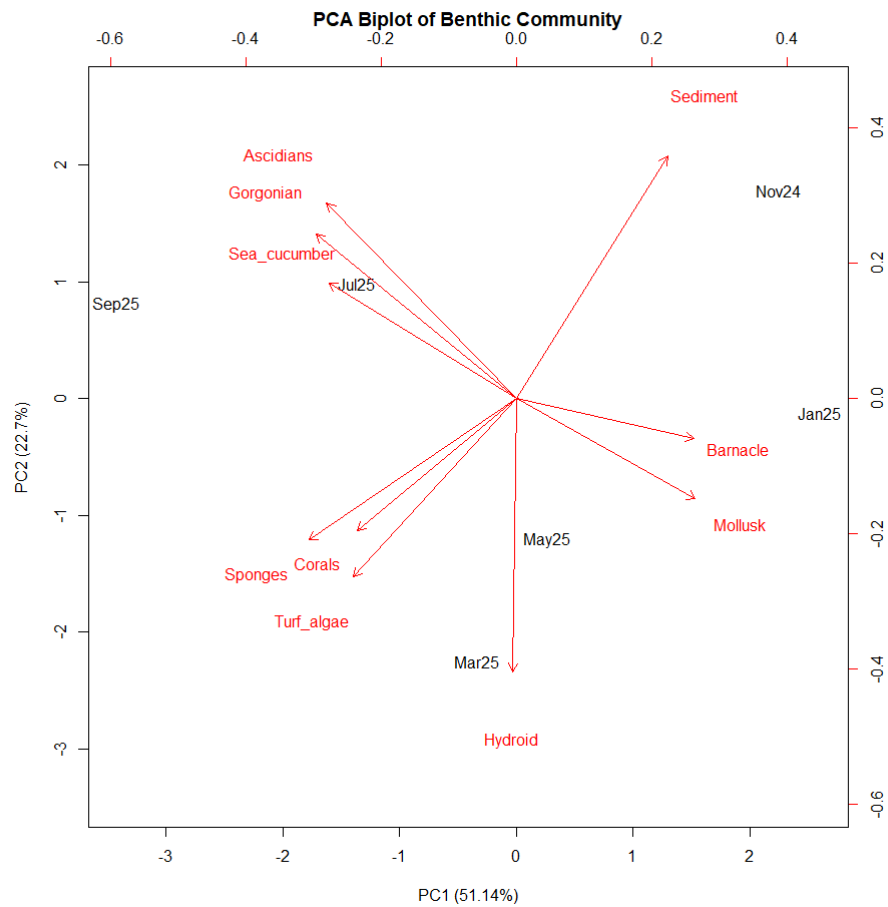


Figure 8 The PCA graph of spatial change of pioneer communities

In addition, algal colonization likely contributes to the inability of coral larvae to settle and grow on the structures (Fricke et al. 2011). However, this study reports observations that had been underwater for only 19 months. Therefore, the findings are not yet definitive for concluding that the structures are unsuitable for coral restoration. Previous studies of sessile organisms on artificial coral reefs have often shown that sessile organisms are found in low numbers during the early stages (1-2 years) (Isdianto et al. 2020) but increase with continued long-term data collection (Frattini et al., 2025; Rallis et al. 2022).

4. Conclusion

A study of the sessile community structure on 3D-printed artificial coral reefs revealed that the majority of the surface remained bare concrete covered with sediment (87.91%), indicating that the community was in the early stages of succession. The first colonizers were turf algae and sponges, showing a continuous increase, especially sponges which had the highest coverage of all benthic organisms, while other benthic organisms increased slightly and exhibited seasonal changes. Meanwhile, coral cover remained very low throughout the study. Regression analysis showed that corals, gorgonians, sponges, and sea cucumbers showed significant increases over time. However, the Friedman test did not show significant differences in distribution between times. Furthermore, the layered structure may trap sediment and promote algal growth, limiting coral larvae settlement.

Considering the results of this study, although the creation of 3D-printed structures primarily intended as coral settlement materials may not be optimal for the settlement of coral recruits, the study collected data only during a 19-month period following the placement of the structures under seawater. Therefore, it is not yet possible to conclude that the surface is unsuitable for coral restoration. Long-term monitoring (3-5 years) should be conducted continuously determine whether such substrates can transition from supporting pioneer assemblages to facilitating coral recruitment and reef restoration functions.

In addition, the application of three-dimensional imaging techniques for assessing sessile organisms and changes in their coverage on artificial substrates represents a promising approach, which may provide more comprehensive insights into community dynamics compared to conventional two-dimensional photographic methods. Furthermore, combining such imaging with data collection on ecological drivers, particularly the grazing rates of herbivorous animals that regulate algal growth, could enhance our understanding of the processes shaping benthic succession.

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