

Spatial Configuration and Multi-trophic Colonization in Modular Artificial Reefs: A Design-Research Field Study for Reef Restoration in the Gulf of Thailand

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Abstract

Artificial reefs are increasingly deployed for coastal restoration, yet design guidance for translating species' spatial requirements into buildable form remains limited. This study field-tests a design-research framework that maps ecological requirements onto three measurable spatial parameters, enclosure, aperture dimensioning, and void orientation, in small-scale modular underwater built environments (UBE).

Four UBE typologies with contrasting spatial configurations were fabricated using low-carbon concrete and 3D printing, then deployed at 6 to 8 m depth off Koh Khai, Chumphon, in the Gulf of Thailand. Fish, invertebrate, and sessile epibiota were monitored across five spatial zones per unit at 30, 60, and 90 days using ordinal abundance and DAFOR scales. Associations were examined with Spearman's rank correlation and Kruskal-Wallis tests.

Colonization increased consistently over time across all typologies ($\rho = 0.44$ to 0.74 , $p < 0.001$). Enclosure predicted the two mobile-versus-cryptic faunal groups in opposite directions, positively for invertebrates ($\rho = +0.34$, $p = 0.008$) and negatively for fish ($\rho = -0.36$, $p = 0.002$). Fish abundance was highest in open zones, whereas invertebrate abundance was highest in enclosed zones.

No single configuration optimized all groups; fish attraction and cryptic-habitat provision were served by structurally distinct designs. These proof-of-concept findings indicate that spatial configuration, including the open space between units, is a design variable that restoration practitioners should specify deliberately, deploying complementary typologies to support multi-trophic biodiversity.

Keyword: Reef Restoration, Artificial Reef, Design Research Methodology, Multi-trophic Colonization, Underwater Built Environment

1. Introduction

Artificial reefs (ARs) are a well-established intervention for restoring degraded marine habitats and supporting coastal livelihoods, using both purpose-built and repurposed materials to mimic the complexity of natural reefs (Ramm et al. 2021; Hein et al. 2019). When strategically deployed, they enhance biodiversity, facilitate coral recruitment, and provide refugia that increase marine biomass (Selig and Bruno 2010; Higgins et al. 2022). Global case studies confirm the efficacy of ARs, with projects such as the Dubai Reef Project and Australia's MARRS reporting substantial gains in coral cover and fish diversity (Paxton et al. 2020; Lange et al. 2024). In Thailand, cross-sector collaborations among government agencies, industry, and local communities have produced measurable ecological recovery at several coastal sites (Monchanin et al. 2021; Kheawwongjan and Kim 2012). Alongside these efforts, a growing movement in ecologically driven reef design has emerged, spanning work on structural complexity (Riera et al. 2024), 3 D-printed habitat structures (Berman et al. 2023), and computational reef typologies (Vogler 2022). Together, these developments point toward closer integration of rigorous design research with marine structural engineering.

Despite these successes, standard artificial reefs remain largely confined to conventional geometries such as cubes, domes, or purely aesthetic biomimetic forms (Vivier et al. 2021), and existing restoration initiatives could be further optimized through site-specific placement and spatial investigation (Yeemin et al. 2006). Structural complexity in coral reefs is a fundamental driver of marine biodiversity and biomass, providing niches and refugia that enhance ecosystem resilience (Graham and Nash 2013). Physical attributes such as crevices, niches, and interstitial voids are vital for the survival of cryptic organisms including shrimp, mollusks, and seahorses (Hixon and Beets 1993). Because marine taxa exhibit distinct spatial requirements (Stella et al. 2011), design must prioritize interconnected networks of voids tailored to target species (Marshall et al. 2025). This approach is grounded in the Refuge Dimensioning hypothesis, which identifies the ratio of opening size to organism body size as a critical determinant of predation-escape success (Rogers et al. 2014). Vertical structural typologies often outperform horizontal ones (Gilliland et al. 2023; Granneman and Steele 2015) by facilitating water flow and nutrient exchange (Zhang et al. 2022), while the establishment of a boundary layer that reduces current velocity within crevices allows small organisms to settle and forage with minimal energy expenditure (Pondella et al. 2022). Fractal, self-repeating geometries further create micro-cavities that harbor cryptic biodiversity such as small crustaceans and gobies (Rouse et al. 2020). Furthermore, roughness significantly improves larval attachment rates by providing stable substrates compared to smooth surfaces (Levenstein 2022). These factors indicate that artificial reef efficacy depends less on sheer structural integrity and more on typologies, nuanced spatial conditions, and precise deployment (Yanovski et al. 2017).

Although modular AR systems favoring smaller, more accessible units have been explored in the same study area (Anonymous 2025), most artificial reefs in Thailand still emphasize structural mass and stability over porosity, open voids, and internal complexity (Monchanin et al. 2021). Shifting the focus from large monolithic structures toward the calibration of scale, porosity, void space, and spatial configuration offers a promising direction for responding more effectively to the needs of target species (Mills et al. 2023).

Contemporary research reinforces this direction. Internal connectivity within reef structures has been shown to raise functional habitat productivity, with complex, void forms sustaining higher productivity than solid, unconnected blocks (Lemoine et al. 2019). Engineered surface heterogeneity and multi-scale texture likewise achieve greater colonization potential than conventional molded or cubic reefs (Perkol-Finkel and Sella 2014), and algorithmic surface complexity in biomimetic tiles has been shown to create niches for cryptic biodiversity (Yu et al. 2025). Together, these findings indicate that embedding spatial complexity and internal voids into small-scale reef design can enhance faunal occupancy and localized ecological resilience (Rouse et al. 2020).

While prior studies have repeatedly shown that structural complexity benefits reef fauna, the field still lacks a systematic method for translating specific biological requirements into concrete, reproducible design parameters, and artificial reefs are often designed intuitively or around fabrication constraints. This study departs from conventional approaches that prioritize structural mass over internal porosity, positioning spatial configuration as the primary independent variable within the Underwater Built Environment (UBE). A UBE is defined here as the sequential assembly of small-scale modular structures, or artificial reefs, configured to engineer marine habitats suited to the vital requirements of micro- and cryptic marine organisms. The design proceeds by mapping the life-history needs of target taxa onto three analytically distinct components: Spatial Typology, Spatial Heterogeneity, and Spatial Connectivity. These components form the design-parameter framework applied across the four UBE typologies investigated in this study.

This study is guided by the research question: what spatial configurations most effectively support the habitation, colonization, and ecological succession of small-scale marine organisms within Underwater Built Environments? To address this, a Design Research Methodology (DRM) framework was adopted (Blessing and Chakrabarti 2009), positioning the investigation as an exploratory Descriptive Study I (DS-I) that uses UBEs as design testbeds, with the resulting typologies evaluated in the field through established visual-census methods. The project was carried out in collaboration with the coastal community of Ban Hin Kob, including a community consultation on the perceived benefits and drawbacks of the deployment, and with experts from Thailand's Department of Marine and Coastal Resources (DMCR) supported the master plan's spatial zoning by identifying optimal placement locations, while also facilitating engagement with local communities. Beyond its research aims, the deployment was intended to contribute to the enhancement of the local underwater environment and to coastal management at the site.

2. Methodology

2.1 Research Design

Following the DS-I designation established above, this study proceeds through three methodological phases. The first phase integrates a systematic literature synthesis with expert-based inquiry, drawing on published evidence in marine habitat ecology, artificial reef performance, and behavioral ecology, together with semi-structured interviews, surveys (English et al. 1997), and focus group discussions with marine biologists, research divers, and local artisanal fishers. Through this process, species-specific spatial requirements were translated into geometric design parameters that link biological habitat needs to UBE structural design decisions.

The second phase comprises UBE typology design and fabrication, in which the spatial parameters derived from Phase 1 were operationalized into four modular typologies differentiated by void geometry, aperture configuration, and enclosure degree. This phase also involved a systematic spatial classification of the Underwater Built Environments, in which each structure was divided into distinct functional zones to allow consistent, part-by-part evaluation. The third phase comprises empirical field monitoring, using SCUBA-based underwater photography and videography together with systematic observer-based review of the resulting imagery (Ninio et al. 2003), to evaluate biological response across the spatially differentiated monitoring zones within each deployed structure.

A quantitative-dominant mixed-methods approach was employed (Creswell and Clark 2018). Quantitative ecological metrics, namely fish and invertebrate abundance (Log4 ordinal scale) (English et al. 1997; Done 1982), sessile epibiota colonization (Modified DAFOR ordinal scale) (Hiscock 1996), and behavioral classification (Rilov and Benayahu 2000), constitute the primary dataset, supplemented by qualitative behavioral observation and contextual field notes (Creswell and Clark 2018). This combination reflects the dual analytical objectives of the study: to quantify ecological performance differences attributable to spatial design variables, and to document organism-structure interactions at sufficient resolution.

Each of the four UBE typologies was deployed as a single unit (n=1 per typology) at a common field site, a constraint imposed by the logistical, monsoon, and financial requirements of underwater concrete fabrication, open-water transportation, and installation. Accordingly, the typology itself is not treated as the unit of statistical replication. Instead, individual spatial monitoring zones within each structure (ranging from 4 to 6 per typology, observed at 30, 60, and 90 days) constitute the observational units for within-typology analyses, yielding 12 to 18 zone-period observations per typology. Consistent with the DS-I designation, this study is oriented toward preliminary trends in the early-stage formation of faunal occupancy rather than long-term succession. Cross-typology comparisons are therefore interpreted as exploratory and hypothesis-generating, with statistical analyses used to identify directional trends and effect sizes that can inform subsequent confirmatory studies, rather than to establish definitive causal attribution.

This study is conducted from an architectural and spatial design perspective. Biological identification is accordingly limited to the family or functional group level; detailed taxonomic, molecular, or physiological analysis falls outside the current scope and is proposed as a primary avenue for future interdisciplinary collaboration.

2.2. study site

The study was conducted at Koh Khai, Pathio District, Chumphon Province, in the central Gulf of Thailand. This location was selected on the guidance of DMCR experts, who identified it as a suitable setting for UBE deployment based on its environmental stability and rehabilitation status. The surrounding waters maintain conditions favorable to reef development, with salinity of 33 to 35 PSU, temperatures of 28 to 30°C, low turbidity, and moderate currents. The site supports reef-associated genera such as *Acropora* and *Porites* and lies within the marine rehabilitation mandate of the Department of Marine and Coastal Resources (DMCR) (Department of Marine and Coastal Resources 2021). This study builds on the authors' earlier work at the same site (Anonymous 2025), extending it from open-void structural investigation toward the spatial-configuration framework developed here. The deployment area is embedded within a broader community-led coral restoration project (Anonymous 2025) and UBE placement was harmonized with the existing artificial reef module alignments of that project. This constraint is acknowledged as a site-specific limitation and addressed in the statistical framing. The precise coordinates and depths of the four monitoring stations are provided in Figure 1 and Table 1.

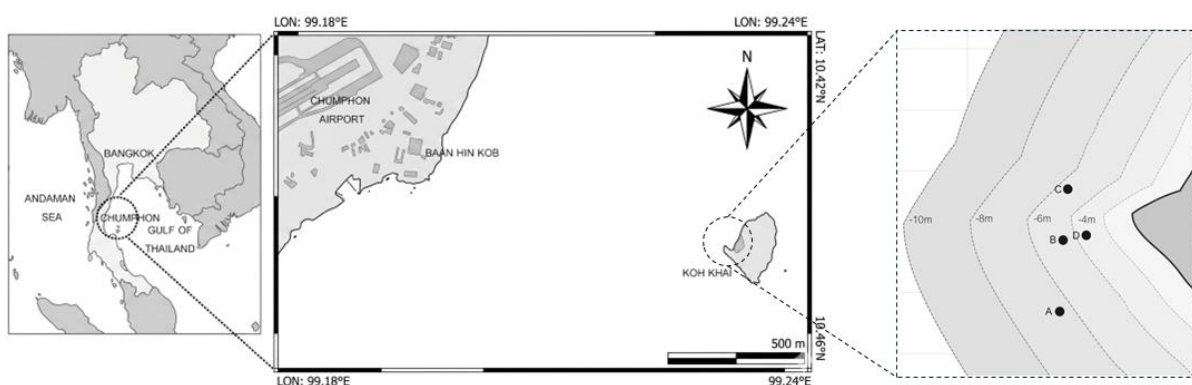


Fig. 1 Location and Installation point, station A-D. site at Koh Khai, Pathio District, Chumphon Province, Thailand (10.55° N, 99.10° E).

Table 1 Table of specific locations of 4 Stations

Station	Latitude (N)	Longitude (E)	Distance from Khai	Depth
A	10° 41.57' N	99° 24.25' E	150 m	8 m
B	10° 42.01' N	99° 24.23' E	140 m	6 m
C	10° 42.00' N	99° 24.25' E	100 m	5 m
D	10° 42.07' N	99° 24.26' E	130 m	6 m

2.3 Underwater Built Environment (UBE) design

2.3.1 The Underwater Ecological-Architectural Synthesis

Synthesizing the literature review and expert inquiries, this analysis identifies the spatial condition typologies suited to the life-history requirements of cryptic fauna in the study area. Dense, small-scale vertical elements suit juvenile shrimp and other small benthic invertebrates (Strain et al. 2018), while heterogeneous crevices provide teleosts with both defensive refugia and territorial surveillance (Taira et al. 2024). For slow-moving taxa such as nudibranchs and gastropods, high-rugosity micro-shelters are essential to mitigate hydraulic dislodgment (Strain et al. 2023). Vertical branching structures facilitate prehensile anchorage for seahorses and pipefish, while large basal cavities combined with narrow, flattened crevices protect brachyuran crabs during molting and satisfy thigmotaxis (Hellyer et al. 2011; Mirera and Moksnes 2015). Vertical porous conduits leverage the Venturi effect to enhance nutrient exchange for polychaetes and sponges (Leys et al. 2011), and strategically sized bottleneck voids exclude larger predators from internal networks (Taira et al. 2024). Evidence further suggests that tiered, layered designs attract higher fish biomass than hollow reef balls by providing size-specific shelters that minimize energy expenditure against ambient currents (Hylkema et al. 2020; Hixon and Beets 1989).

By translating these species-specific behaviors into physical design parameters, this research transitions from descriptive ecological study toward architectural design intervention. These parameters operationalize the three spatial design components: Spatial Typology defines the overall void geometry in relation to target taxa; Spatial Heterogeneity addresses the varied ways in which different organisms respond to spatial form; and Spatial Connectivity links internal spaces, a factor essential to the survival and daily functioning of marine organisms. Together, these considerations guide the configuration of each station in the subsequent phase.

2.3.2 The Four UBE Typologies: From Synthesis to Spatial Form

Building on the design components above, the synthesized biological requirements were translated into four UBE typologies, each expressing a distinct spatial principle through a specific set of dimensions (Table 2). All units were sized for manual transport and community-led installation.

Station A. Randomized Lithic-Mimicry. A base layer of small modular reef units (approximately 25 cm high) supports an upper assembly of randomly oriented rock fragments (5 to 15 cm), reaching a total height of about 35 to 40 cm. The resulting voids are irregular, ranging from narrow gaps of about 5 cm to wider interstitial pockets of 8 to 20 cm depending on packing density. This typology expresses the Complex Interstitial Labyrinths principle, providing a multi-layered, sub-lithic crevice network suited to cryptic, predator-avoidant fauna such as brachyurans and mollusks.

Station B. Tiered Interconnected Refugia. This station reaches a total height of about 76 cm, organized into four stacked concrete tiers of roughly 19 cm each. Internal voids are consistently about 17 cm wide, with a stepped footprint expanding from about 50 cm at the upper tiers to 100 cm at the base. This layered geometry expresses the Hierarchical Horizontal Tiered Shelters principle, its graduated clearance heights accommodating a range of body sizes, from narrow-crevice brachyurans and cephalopods to larger demersal fish requiring deeper lateral recesses.

Station C. Vertical Cavities. Standing about 55 to 60 cm high, this station comprises a stabilized base module (about 22.5 cm) and a habitat-pod array (about 30 to 35 cm), separated by internal voids of 5 to 8 cm, with vertical apertures distributed across a horizontal span of 20 to 30 cm. These narrow, evenly spaced vertical channels express the Vertical Circulation Conduits principle, using chimney-aperture geometry to drive Venturi-based vertical water exchange. This flow limits sediment accumulation and supplies oxygenated, nutrient-rich water to sessile colonizers such as sponges and tube worms, while supporting coral-larval attachment.

Station D. Horizontal Stratification Cavity. This station measures about 70 to 72 cm in total stacking height, built from interlocking triangular modules of 35 cm each. The assembly generates cavities of 7 to 22 cm in height, ranging from benthic-adjacent openings to mid-water channels up to 32 cm deep. This low-relief geometry expresses the Horizontal Through-Passages and Flow-Through Cavities principle, its unobstructed lateral apertures enabling laminar flow-through that minimizes drag while delivering planktonic food to filter-feeding rheophiles such as small fish, gorgonians, and crinoids.

The four UBE prototypes were developed around four design criteria established in earlier work: Modularity, Surface Complexity, Structural Stability, and Habitat Creation (Anonymous 2025). Each station comprises small-scale modular blocks interconnected in an interlocking assembly, sized so that scale, morphology, and void distribution can be adjusted per typology while remaining affordable and installable by the coastal community without heavy machinery (Figure 2; full specifications in Table 3).

Table 2. Spatial Design Component Matrix across Four UBE Typologies

Typology	Spatial Typology	Heterogeneity	Connectivity
A Randomized Lithic-Mimicry	Labyrinthine internal cavities; lithic-plate overlap	High: fractal recesses at multiple scales	Moderate: interconnected internal crevices
B Tiered Interconnected Refugia	Tiered lateral recesses; varied clearance heights	High: multi-level voids for varied size-classes	High: continuous internal pathways to seabed and wall
C Vertical Cavities	Vertical chimney-aperture voids	Moderate: internal vs. external differentiation	Moderate: vertical conduits, open spaces between structures
D Horizontal Stratification	Horizontal through-passages; shallow voids	Low-Moderate: mainly horizontal plane	Low: open lateral apertures, minimal linkage

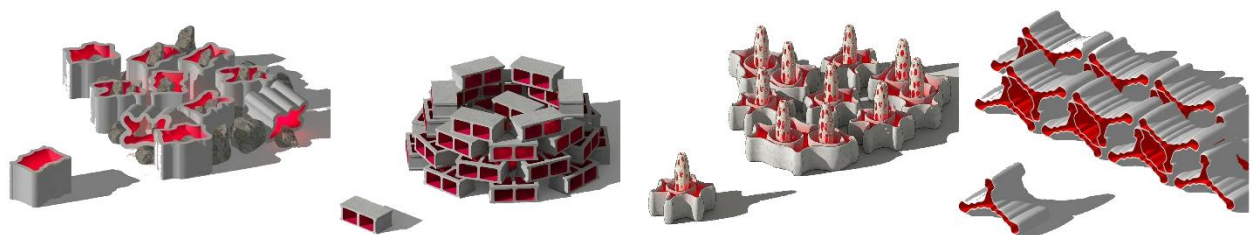
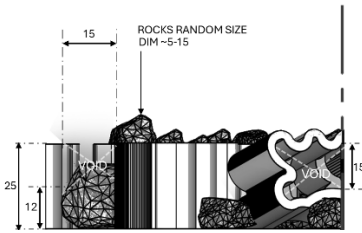
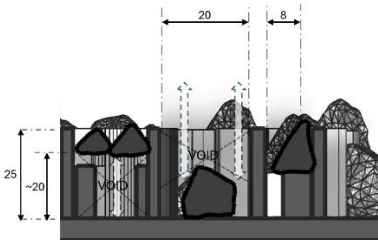
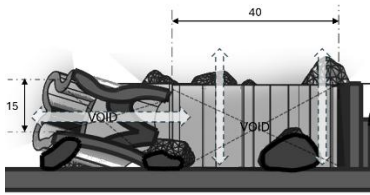
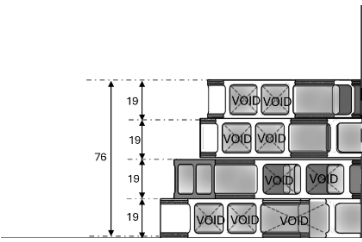
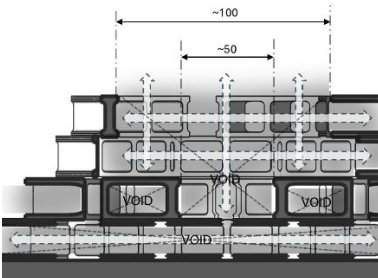
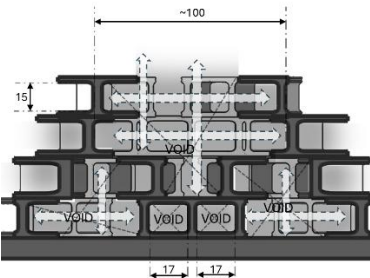
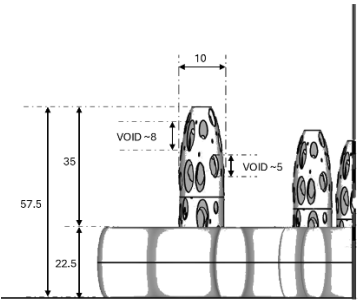
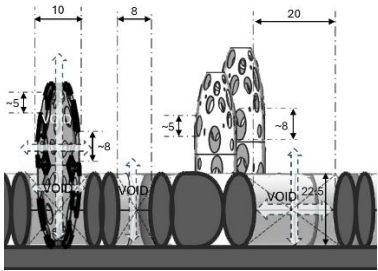
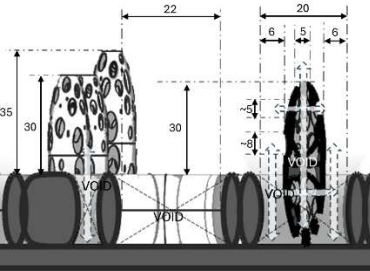
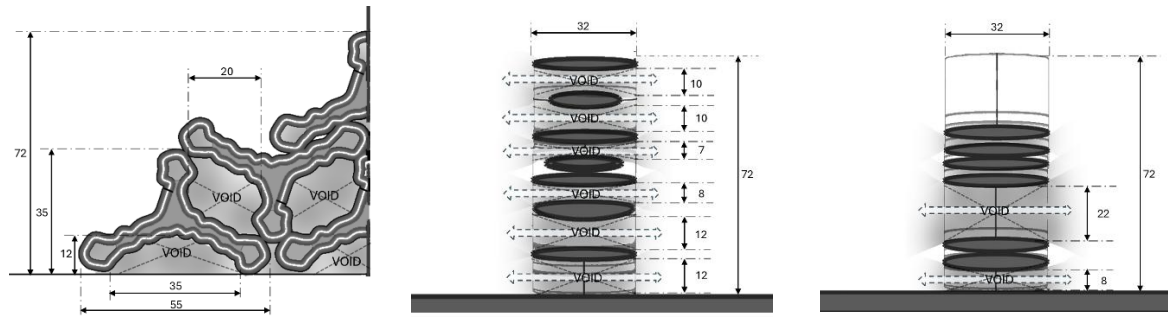


Fig. 2 3D visualizations of four UBE typologies, highlighting internal void configurations. From left to right: Station A, Station B, Station C, and Station D.

249 **Table 3.** Void Dimensioning and Aperture Parameters across Four UBE Typologies. All dimensions in
250 centimeters (cm).
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Elevation	Section 1	Section 2
Station A — Randomized Lithic-Mimicry		
		
Station B — Tiered Interconnected Refugia		
		
Station C — Vertical Cavities		
		
Station D — Horizontal Stratification Cavity		



2.4 Fabrication and Field Deployment

The four prototypes were fabricated using different methods according to research objectives and material availability (Figure 3). Station A was produced by 3D concrete printing with SCG-LW250 low-carbon concrete, whose layered deposition creates a high-rugosity texture. Station B used parametrically modeled concrete blocks assembled into hierarchically nested configurations, avoiding the geometric limits of large-scale 3D printing (Gardiner 2011). Station C followed a hybrid approach, combining a 3D-printed base with cast-concrete vertical modules. Station D used 3D-printed triangular units designed for stable stacking. Across all typologies, fabrication prioritized structural integrity, transportable weight, and ecological safety, and each assembly was tested before field installation.

Deployment was carried out at Koh Khai reef between October 2025 and June 2026. Units were installed by hand from local fishing vessels at depths of 6 to 8 m, oriented to seasonal nutrient-carrying currents, using low-impact anchoring on sandy substrates to avoid existing coral colonies. Systematic inter-station spacing was maintained for comparative monitoring. The deployment process is illustrated in Figure 4.



Fig. 3 Fabricated structure prototypes of the four UBE typologies.

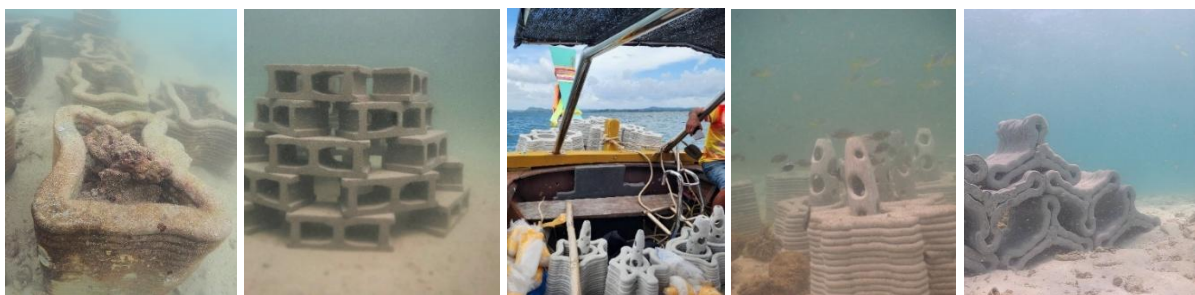


Fig. 4 Image showing the Field Deployment and Installation process.

2.5 Ecological Monitoring Framework

This research evaluates the ecological performance and spatial habitat preferences of the four UBE typologies (Stations A to D) at 30, 60, and 90 days. Underwater data were collected via SCUBA-based photography and videography, and all imagery was reviewed by the observer to assess the relationship between architectural configuration and faunal response.

2.5.1 Classification Criteria for Macro-Fauna

Organisms were classified using the Functional Group Approach (Bohnsack and Sutherland 1985), prioritizing total biomass and population density in response to UBE structural variables over species-level identification. Three functional groups were defined by physical traits and habitat use:

- Fish (pelagic and demersal): treated as a single functional unit to quantify total fish biomass and spatial distribution, encompassing migratory species, transient visitors, and residents interacting with the water column and structural voids (Hylkema et al. 2020).
- Benthic macroinvertebrates: categorized by biological form and microhabitat use within crevices or the adjacent seabed, comprising mollusks (bivalves and gastropods), crustaceans (crabs and shrimps), echinoderms (sea urchins and starfish), and annelids (polychaetes) (Strain et al. 2018; Wang et al. 2025).
- Sessile epibiota (coral recruits and encrusting algae): representing the primary ecological succession on UBE surfaces, comprising scleractinian coral recruits, which indicate long-term structural accretion, and encrusting algae (Whalan et al. 2015; Muñoz-Maravilla and Edmunds 2025).

2.5.2 Survey Protocols and Data Collection

Data collection prioritizes population density and spatial mapping over individual biomass measurement, in order to identify how specific architectural features influence each functional group. Key metrics include Frequency of Occurrence (for mobile fauna) and ecological succession of coral recruitment, used to determine substrate orientation preferences. Three survey protocols were applied, corresponding to the three functional groups defined above:

- Fish abundance and spatial distribution were quantified using the Stationary Visual Census (SVC) technique (English et al. 1997). A diver surveyed a cylindrical volume (5–7 m radius) from a fixed point for 5–10 minutes, recording fish interacting with open voids, peripheral zones, and the upper surfaces of the UBE structure. To mitigate observer bias during high-density encounters, abundance was recorded using the Log₄ ordinal scale (Table 4) (English et al. 1997).
- Benthic macroinvertebrate occupancy — specifically mollusks, crustaceans, and polychaetes inhabiting internal cavities and sheltered recesses — was assessed via quadrat sampling (0.25–1.0 m²) (English et al. 1997). Quadrats were strategically placed across structurally distinct UBE surfaces (e.g., internal voids versus exterior planes) to correlate organism presence with local structural complexity (Strain et al. 2018; Wang et al. 2025). Density was likewise categorized using the Log₄ abundance scale (English et al. 1997).
- Ecological succession and coral recruitment were evaluated using Spatial Preference Profiling combined with a Modified DAFOR Ordinal Scale (Table 5), adopted in order to align with the design-oriented framework of this study and to mitigate the optical distortion inherent in conventional 2D percent-cover metrics when applied to complex 3D structures (Whalan et al. 2015; Muñoz-Maravilla and Edmunds 2025).

This semi-quantitative visual abundance framework was adapted from established reef monitoring protocols (Hill and Wilkinson 2004) and modified to suit micro-spatial built environments. The five-level visual assessment scale categorizes the density of biological colonization based on physical

indicators and substrate visibility, shifting the analytical focus from overall surface-area calculation toward structural niche performance and spatial preference. The summary of Ecological Monitoring Framework indicated in Table 6.

Table 4 Table of log4 abundance scale.

Abundance Scale	Number of Individuals	Estimated Value
1	1	1
2	2 - 4	3
3	5 - 16	10
4	17 - 64	40
5	65 - 256	160
6	257 - 1,024	640

Table 5 Table of Modified DAFOR Ordinal Scale

Scale	Rating	Physical Criteria / Visual Indicators
1	Scarce / Absent	No recruitment observed, or only 1–2 highly isolated individuals across the zone.
2	Sparse	Low-density colonization occurring in scattered spots; the original material remains highly visible and dominant.
3	Moderate	Evenly distributed colonization; initial clusters or groupings of coral begin to form visibly.
4	Abundant	High-density colonization across the designated area, substantially obscuring the original substrate structure.
5	Dominant	The spatial niche (void or plane) is completely colonized; the original material is entirely obscured by coral growth.

Table 6 Table of Semi-Quantitative Abundance Scale

Target Group	Survey Technique	Spatial Scope	Key Metrics	Measurement Scale
1. Fish Assemblages	Stationary Visual (SVC)	Cylindrical Volume	Taxa Identification, Quantity	Log4 Scale
2. Benthic Macrofauna	Targeted Sampling	Internal Cavities & Exterior	Taxa Identification, Quantity	Log4 Scale
3. Sessile Epibiota	High-Res Photo-a	Substrate Surfaces	Recruitment Density	Modified DAFOR Ordinal Scale

2.6 Data Analysis: Spatial Classification and Habitat Behavior

The analysis is organized into three criteria: the spatial reference and positioning of each UBE zone, the biological composition (fish biomass and coral-larval patterns), and the behavioral and structural interactions between organisms and the UBE.

2.6.1 Classification of Spatial Reference and Positioning

Spatial references within the UBE structures were categorized by geometric properties and microhabitat function. This classification defines the study's independent variables, enabling analysis of

how specific architectural niches influence faunal occupancy and behavior. The spatial matrix comprises five primary zones:

- 1) Internal Voids and Cavities (Refugia): enclosed or semi-enclosed spaces within the UBE that shelter cryptic and resident species from predation and high-energy currents (DeVantier and Turak 2020).
- 2) Exterior Planes and Surfaces, sub-categorized into (2.1) Upper Planes, exposed to direct vertical light and promoting photophilic growth such as coral recruits (Carral et al. 2022), and (2.2) Lower Planes, shaded areas preferred by sciaphilic organisms (Wedding et al. 2011).
- 3) Directional Voids (Vertical and Horizontal): transition spaces analyzed by orientation, comprising (3.1) Vertical Voids (upper/lower), channels facilitating vertical water flow and nutrient transport (Leys et al. 2011), and (3.2) Horizontal Voids (ceiling/floor), sheltered interfaces where ceiling surfaces provide recruitment sites protected from sedimentation (Carral et al. 2022).
- 4) Structural / Seabed Interface: the contact zone between the UBE base and the natural seabed, where foraging and scouring-induced biodiversity transitions are observed.
- 5) Surrounding Vicinity (Water Column): the immediate fluid environment around the structure (upper and lateral zones), used by migratory pelagics and schooling fish as a focal point.

2.6.2 Classification of Marine Habitat behavior Patterns

Marine organisms observed within the UBE structures are categorized into three behavioral groups based on site utilization and structural dependency, following established reef-fish behavioral classification frameworks (Hylkema et al. 2020):

- 1) Migratory Species: Primarily pelagic schooling fish, such as planktivores. These species typically pass through the UBE area while traveling in the water column and do not rely directly on the physical structures.
- 2) Temporal Visitors: Occasional visitors that enter the area to feed on organisms found in the surrounding sand, algae, or biofouling on the structures. This group utilizes the reef habitat for temporary shelter or foraging.
- 3) Resident Species: Permanent inhabitants that remain within the UBE site. These fish stay close to the structures, utilizing crevices, holes, and surface-dwelling organisms for habitat and direct sustenance.

Based on this classification, spatial configuration serves as the independent variable of the study, operationalized through the enclosure, orientation, and connectivity of the spatial zones defined above. The dependent variables are faunal abundance (at the functional-group or family level), population density, and behavioral occupancy patterns.

2.7 Marine Habitat performance: Spatial Classification of Underwater Built Environments (UBEs)

Each of the four stations was divided into spatial zones according to its physical morphology and structural orientation, following the zone definitions established in Section 2.6.1. As the stations differ in geometry, they present distinct subsets of these zones; vertical voids, for instance, occur only in Station C, whereas horizontal voids are present in Stations B and D. The complete zone composition of each station is summarized in Table 7, with the corresponding zone overlays shown in Figures 5.

Table 7 Table of Spatial Classification of all UBE station

Spatial Zones	Station A	Station B	Station C	Station D
1. Internal Cavities / Voids	●	●		
2. Exterior Planes (2.1 Upper / 2.2 Lower)	●	●	●	●
3. Horizontal Voids (3.1 Ceiling / 3.2 Floor)		●		●
4. Vertical Voids (4.1 Upper / 4.2 Lower)			●	
5. Structural / Seabed-UBE Interface	●	●	●	●
6. Surrounding Vicinity	●	●	●	●

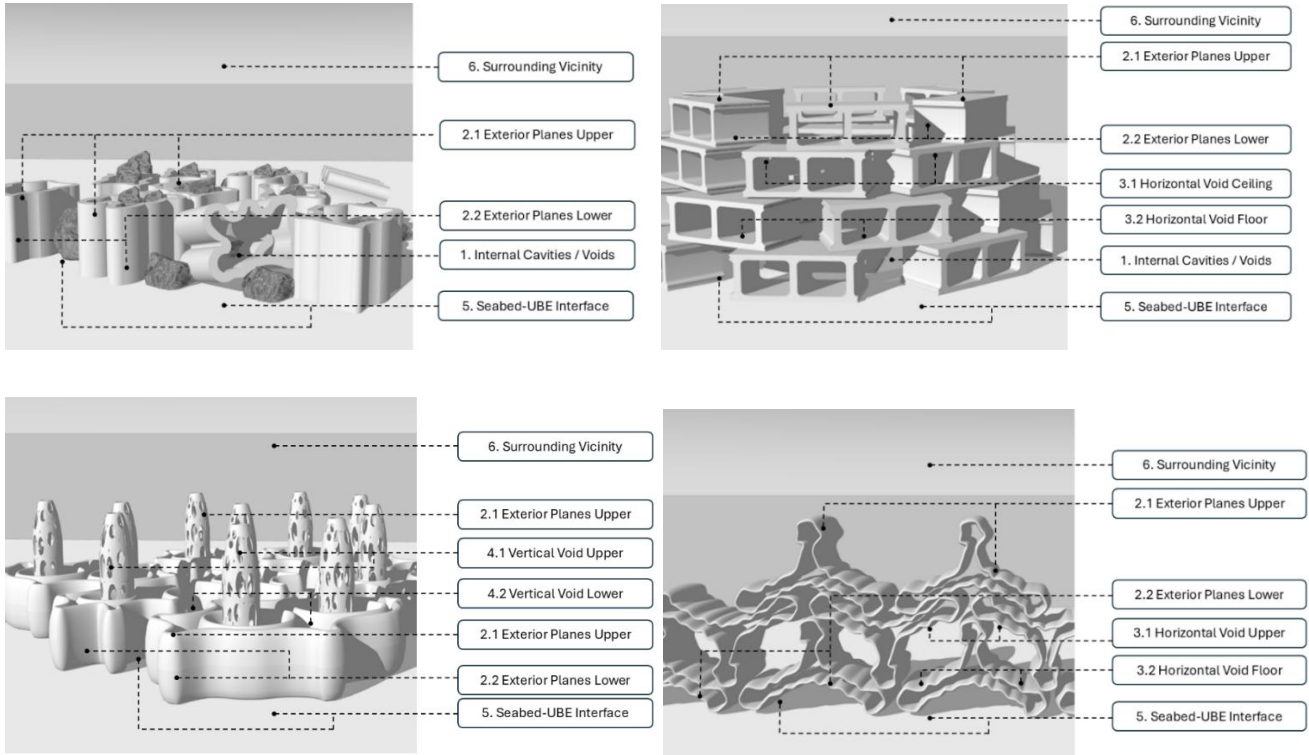


Fig 5. Spatial zone classification overlaid on Station A - D, showing Internal Cavities/Voids, Exterior Planes (Upper/Lower), Structural/Seabed Interface, and Surrounding Vicinity.

3. Results

Field observations were collected at 30, 60, and 90 days and assessed from underwater imagery (Figure 6) to quantify faunal abundance and coral-larval settlement across the four stations. The following sections present these results by station and then compare responses across typologies



Fig 6. Representative underwater imagery used for visual assessment of faunal abundance and substrate colonization.

3.1 Faunal Colonization and Habitat Utilization Across Typologies

Faunal responses were recorded using three ordinal measures applied consistently across all stations. Fish and invertebrate abundance were scored on a Log4 ordinal scale (1 = 1–3, 2 = 4–10, 3 = 11–40, 4 = 41–160, 5 = 161–640 estimated individuals), and sessile epibiota were scored on a Modified DAFOR scale (1 = Rare, 2 = Occasional, 3 = Frequent, 4 = Abundant, 5 = Dominant). Behavioral classification is reported as fish behavior / invertebrate behavior, where Res = Resident, TV = Temporal Visitor, and Mig = Migratory. A dash (—) denotes not recorded. These conventions apply to all station-level tables that follow (Tables 8 to 19). The following sections present each station in turn.

3.1.1 Station A — Randomized Lithic-Mimicry

Station A showed a progressive colonization sequence in which cryptic invertebrates preceded stable fish residency. By day 60, benthic invertebrates in the internal cavities had reached resident status while fish were still transitioning, and sessile epibiota in these cavities were already the most advanced of any zone. By day 90, the internal cavities were fully occupied by both resident fish and invertebrates, and sessile cover there reached the maximum DAFOR score, while exterior planes and the seabed interface followed the same trajectory more slowly. Fish abundance in the surrounding vicinity was consistently the highest of any zone and peaked at day 90, a pattern more consistent with aggregate attraction to a maturing unit than with occupancy of the structure itself (Tables 8 - 10).

Table 8. Log4 ordinal scale by spatial zone - Station A

Spatial zone	Fish abundance (Log4 estimated individuals)			Benthic macroinvertebrates (estimated individuals)		
	30 days	60 days	90 days	30 days	60 days	90 days
Internal Cavities	10	10	40	3	10	10
Exterior Upper	10	10	40	1	3	10
Exterior Lower	10	10	40	3	3	10
Seabed Interface	3	10	40	3	10	10
Surrounding vicinity	40	40	160	—	—	—

Table 9. Modified DAFOR score by spatial zone - Station A

Spatial zone	30 days	60 days	90 days
Internal Cavities	3	4	5
Exterior Upper	1	2	3
Exterior Lower	1	2	3
Seabed Interface	1	2	3

Table 10. Fish / invertebrate behavior by spatial zone - Station A

Spatial zone	30 days	60 days	90 days
Internal Cavities	TV / TV	TV / Res	Res / Res
Exterior Upper	Mig / Mig	TV / TV	TV / TV
Exterior Lower	Mig / Mig	TV / Res	TV / Res
Seabed Interface	Mig / TV	TV / Res	TV / Res

3.1.2 Station B — Tiered Interconnected Refugia

Station B showed markedly faster invertebrate colonization than Station A. Resident benthic invertebrates occupied the horizontal void zones by day 30, a level Station A did not reach until day 60, consistent with the preference of brachyuran crabs and small crustaceans for protected, low-clearance passages; octopus residency was also observed within the seabed void channels. Internal cavities progressed to full resident status for both fish and invertebrates by day 60. Sessile colonization concentrated on the horizontal ceiling voids and the light-exposed upper planes, both reaching the maximum DAFOR score by day 90, whereas the shaded internal cavities and floor voids remained lower. This vertical separation of sessile cover, ceiling and upper surfaces high, enclosed lower voids low, indicates that light exposure and sedimentation shelter shaped colonization within a single structure (Tables 11 to 13).

Table 11. Log4 ordinal scale by spatial zone - Station B

Spatial zone	Fish abundance (Log4 estimated individuals)			Benthic macroinvertebrates (estimated individuals)		
	30 days	60 days	90 days	30 days	60 days	90 days
Internal Cavities	10	40	40	3	10	40
Exterior Upper	10	10	10	0	1	3
Exterior Lower	10	10	10	1	1	3
H-Void Ceiling	3	10	10	10	10	40
H-Void Floor	3	10	10	10	10	40

Seabed Interface	3	10	10	3	10	10
Surrounding vicinity	40	40	160	—	—	—

Table 12. Modified DAFOR score by spatial zone - Station B

Spatial zone	30 days	60 days	90 days
Internal Cavities	1	2	3
Exterior Upper	2	4	5
Exterior Lower	1	2	3
H-Void Ceiling	2	4	5
H-Void Floor	1	2	3
Seabed Interface	2	3	4

Table 13. Fish / invertebrate behavior by spatial zone - Station B

Spatial zone	30 days	60 days	90 days
Internal Cavities	TV / TV	Res / Res	Res / Res
Exterior Upper	Mig / —	TV / TV	TV / TV
Exterior Lower	Mig / Mig	TV / TV	TV / TV
H-Void Ceiling	TV / Res	Res / Res	Res / Res
H-Void Floor	TV / Res	Res / Res	Res / Res
Seabed Interface	Mig / Mig	TV / TV	TV / TV

3.1.3 Station C — Vertical Cavities

Station C, which has low enclosed internal cavities but presents open vertical void channels, produced a biologically distinct profile. Its most salient feature was the rapid, sustained colonization of the vertical voids by benthic invertebrates: resident invertebrates occupied the lower vertical voids as early as day 30, before fish residency was established anywhere in the structure, and both upper and lower vertical voids reached the maximum sessile DAFOR score by day 90. This bottom-up sequence, in which invertebrate settlement preceded fish residency, indicates that colonization here was driven by the void geometry itself rather than by fish attraction to structural complexity. Fish remained largely migratory at day 30 and reached their highest abundance only in the exterior planes and surrounding vicinity by day 90 (Tables 14 to 16).

Table 14. Log4 ordinal scale by spatial zone - Station C

Spatial zone	Fish abundance (Log4 estimated individuals)			Benthic macroinvertebrates (estimated individuals)		
	30 days	60 days	90 days	30 days	60 days	90 days
Exterior Upper	10	10	40	10	10	40
Exterior Lower	3	10	10	3	10	10
Vertical Void Upper	3	10	10	3	10	40
Vertical Void Lower	1	3	10	10	10	40
Seabed Interface	3	3	10	3	3	10
Surrounding vicinity	40	40	160	—	—	—

Table 15. Modified DAFOR score by spatial zone - Station C

Spatial zone	30 days	60 days	90 days
Exterior Upper	2	4	4
Exterior Lower	1	2	3
Vertical Void Upper	3	4	5
Vertical Void Lower	3	4	5
Seabed Interface	1	2	3

Table 16. Fish / invertebrate behavior by spatial zone - Station C

Spatial zone	30 days	60 days	90 days
Exterior Upper	Mig / TV	TV / TV	TV / Res
Exterior Lower	Mig / TV	TV / TV	TV / TV
Vertical Void Upper	Mig / TV	TV / Res	TV / Res
Vertical Void Lower	Mig / Res	TV / Res	TV / Res
Seabed Interface	Mig / TV	TV / TV	TV / Res

3.1.4 Station D — Horizontal Stratification Cavity

Station D recorded the highest absolute fish abundance in the study, with exterior planes and the surrounding vicinity reaching the maximum abundance level by day 90, consistent with a broad, flat, high-visibility geometry that maximizes attraction of migratory and transient fish. Invertebrate colonization, by contrast, was the most limited of the four stations: exterior planes held no invertebrates at day 30 and remained low throughout, and only the horizontal ceiling voids and seabed interface progressed to resident invertebrate status by day 90. Sessile cover was highest on the light-exposed upper planes, reaching the maximum DAFOR score, while the enclosed horizontal voids remained lower. This divergence, abundant fish but sparse invertebrates, marks Station D as attraction-dominated rather than supporting broad multi-trophic establishment (Tables 17 -19).

Table 17. Log4 ordinal scale by spatial zone - Station D

Spatial zone	Fish abundance (Log4 estimated individuals)			Benthic macroinvertebrates (estimated individuals)		
	30 days	60 days	90 days	30 days	60 days	90 days
Exterior Upper	40	40	160	0	3	10
Exterior Lower	40	40	160	0	3	10
H-Void Ceiling	10	40	40	1	3	3
H-Void Floor	10	40	40	1	3	10
Seabed Interface	10	40	40	1	3	3
Surrounding vicinity	40	160	160	—	—	—

Table 18. Modified DAFOR score by spatial zone - Station D

Spatial zone	30 days	60 days	90 days
Exterior Upper	2	3	5
Exterior Lower	2	3	4
H-Void Ceiling	1	2	3
H-Void Floor	1	2	3
Seabed Interface	2	3	4

Table 19. Fish / invertebrate behavior by spatial zone - Station D

Spatial zone	30 days	60 days	90 days
Exterior Upper	Mig / —	TV / TV	TV / TV
Exterior Lower	Mig / —	TV / TV	TV / TV
H-Void Ceiling	TV / TV	Res / TV	Res / Res
H-Void Floor	TV / TV	Res / TV	Res / Res
Seabed Interface	Mig / Mig	TV / TV	TV / Res

3.2 Spatial Zone Classification and Ecological Response Matrix — UBE Monitoring, Koh Khai, Chumphon (90 days)

Table 20 consolidates the 90-day endpoint across all four stations, cross-referencing each spatial zone's enclosure level, dominant fauna, and behavioral classification. This allows structurally analogous zones, such as enclosed internal voids or open exterior surfaces, to be compared across typologies. A consistent behavioral trajectory was evident across all stations: zones were dominated by migratory fish at 30 days, shifted toward temporal-visitor behavior by 60 days, and reached resident occupancy most rapidly in enclosed or sheltered zones. This progression from transient attraction to stable residency provides an observable proxy for habitat maturation across the four typologies.

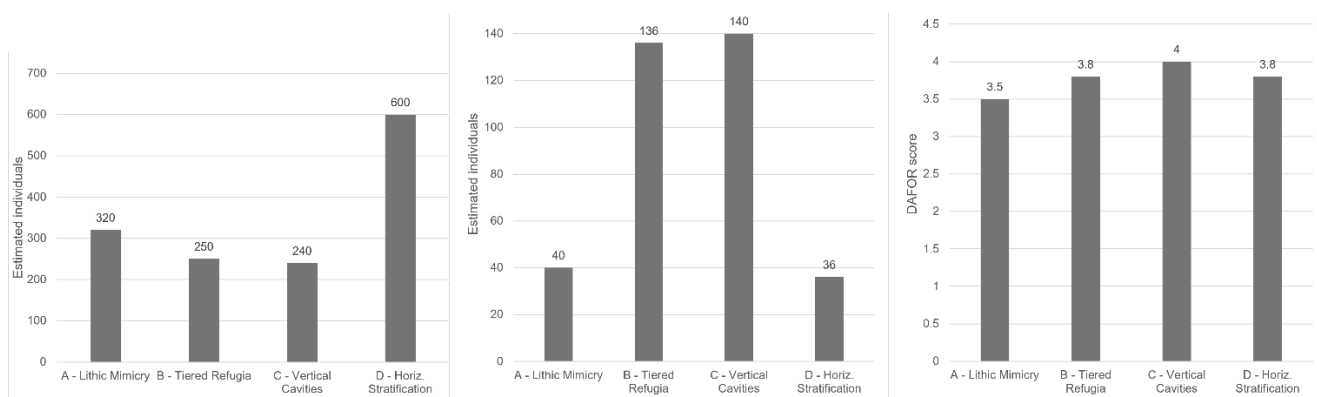
At the 90-day endpoint, the four typologies diverged most clearly in the opposing patterns of fish and invertebrate abundance (Figure 11). Station D recorded the highest fish abundance but the lowest invertebrate abundance, whereas Stations B and C showed the reverse. Average sessile DAFOR scores, by contrast, remained similar across all stations. This inverse relationship between fish and invertebrate abundance is examined statistically in the following section.

Table 20. Stations A–D: enclosure level, dominant fauna, and behavioral classification at the 90-day endpoint.

Spatial Zone	Enclosure level	Dominant fauna	Behavioral class (90 d)
Station A — Randomized Lithic-Mimicry			
Internal cavities	Enclosed	Cryptic fish, crabs, mollusks	Resident (from day 60)
Inter-structural voids / exterior walls	Semi-exposed	Small teleosts, sea urchins	Temporal visitor
Surrounding vicinity	Open	Schooling fish	Migratory transit
Station B — Tiered Interconnected Refugia			
Internal connected voids	Enclosed	Small fish, cephalopods	Resident (from day 60)
H-void ceiling	Semi-enclosed	Sciaphilic sessile, coral recruits	Resident sessile (from day 30)
H-void floor / seabed interface	Semi-enclosed	Crabs, juvenile shrimp, cryptic fish	Resident (from day 30)
Exterior upper surfaces	Exposed	Algal turf, coral recruits	Temporal visitor (fish)
Station C — Vertical Cavities			
Internal vertical capsules (upper void)	Enclosed (chimney aperture)	Coral recruits, small circulating fish	TV → resident (fish from day 60)

Internal vertical interstices (lower base)	Enclosed (narrow crevice)	Polychaetes, mollusks	Resident (from day 30)
Vertical-to-base transition	Semi-enclosed	Sea urchins, polychaetes	Resident (invertebrates)
External inter-structural vertical voids	Semi-exposed	Diverse small-scale fish	Residency + transit
General external perimeter	Open (vertical relief)	Large schooling fish	Migratory transit
Station D — Horizontal Stratification Cavity			
H-void ceiling	Semi-enclosed (ceiling)	Algal turf (sciaphilic)	Sessile (from day 60)
H-void floor / shallow refuge	Semi-enclosed (floor)	Juvenile and small schooling fish	Resident (from day 30)
Exterior upper surfaces / stacked modules	Exposed	Algal turf, transient fish	Temporal visitor (fish)
Surrounding vicinity	Open	Large schooling and migratory fish	Migratory (highest abundance)

Fig 11. Total fish abundance, invertebrate abundance, and average DAFOR score across the four typologies at the 90-day endpoint. Fish abundance includes surrounding-vicinity counts. DAFOR = Modified DAFOR ordinal scale (1 = Rare to 5 = Dominant). Invertebrate counts represent the sum across all spatial zones.



3.3 Statistical Analysis

Spearman's rank correlation and Kruskal-Wallis H tests were applied to the pooled zone-level dataset using Log4-derived abundance values and Modified DAFOR ordinal scores. Fish analyses include the surrounding-vicinity zone (n = 72); invertebrate and sessile analyses exclude it, as these were not recorded there (n = 59-60). Enclosure was coded ordinally (3 = enclosed, 2 = semi-enclosed, 1 = open). Given the single-unit deployment (n = 1 per typology), these analyses are treated as exploratory associations characterizing the observed dataset rather than confirmatory inferential tests.

3.3.1 Spearman's Rank Correlation

Time period correlated strongly and positively with all three biological metrics ($\rho = 0.44$ to 0.74 , all $p < 0.001$), confirming a consistent colonization trajectory across the four typologies over the monitoring period (Table 21). Enclosure level showed opposing

associations between the two mobile-versus-cryptic faunal groups: a significant negative correlation with fish abundance ($\rho = -0.36$, $p = 0.002$) and a significant positive correlation with invertebrate abundance ($\rho = +0.34$, $p = 0.008$). This inverse pattern indicates that fish and cryptic invertebrates are favored by structurally opposite conditions, open exposure and enclosure respectively. Enclosure was not significantly correlated with sessile DAFOR score ($\rho = 0.18$, $p = 0.170$), suggesting that sessile colonization is shaped less by enclosure than by other factors such as surface orientation. Invertebrate abundance and DAFOR score were positively associated ($\rho = 0.56$, $p < 0.001$), whereas fish and invertebrate abundance were not ($\rho = 0.08$, $p = 0.571$), consistent with the distinct ecological drivers proposed for mobile and sessile or cryptic taxa.

Table 21. Spearman's rank correlation between structural/temporal variables and biological response metrics (pooled zone-level data, all stations)

Variable pair	ρ	p-value	n	Sig.
Time period vs. Fish abundance	0.44	< 0.001	72	**
Time period vs. Invertebrate abundance	0.60	< 0.001	59	**
Time period vs. DAFOR score	0.74	< 0.001	60	**
Enclosure level vs. Fish abundance	-0.36	0.002	72	*
Enclosure level vs. Invertebrate abundance	0.34	0.008	59	*
Enclosure level vs. DAFOR score	0.18	0.170	60	ns
Fish abundance vs. Invertebrate abundance	0.08	0.571	59	ns
Invertebrate abundance vs. DAFOR score	0.56	< 0.001	59	**
Fish abundance vs. DAFOR score	0.29	0.023	60	*

Significance: ** $p < 0.001$; * $p < 0.05$; ns = not significant. Enclosure level coded ordinally (3 = Enclosed, 2 = Semi-enclosed, 1 = Open/Exposed).

3.3.2 Kruskal-Wallis H Test

Comparisons across the four station typologies revealed significant differences in fish abundance ($H = 14.99$, $p = 0.002$) and invertebrate abundance ($H = 10.59$, $p = 0.014$), but not in DAFOR score ($H = 1.63$, $p = 0.653$), indicating that structural differentiation shaped mobile and cryptic fauna more than sessile recruitment (Table 22). Grouping all zones by enclosure category, independent of station, corroborated the divergent pattern: fish abundance differed significantly by enclosure level, with the highest median in open zones ($H = 9.90$, $p = 0.007$), while invertebrate abundance also differed significantly, with the highest median in enclosed zones ($H = 7.11$, $p = 0.029$) (Table 23).

Table 22. Kruskal-Wallis H test comparing biological response metrics across the four UBE station typologies (pooled across 30/60/90-day monitoring periods)

Metric	H	p-value	Median A	Median B	Median C	Median D
Fish abundance	14.99	0.002 *	10	10	10	40
Invertebrate abundance	10.59	0.014 *	6.5	10	10	3
DAFOR score (sessile epibiota)	1.63	0.653 ns	2.5	2.5	3.0	3.0

Significance: ** $p < 0.001$; * $p < 0.05$; ns = not significant. A = Randomized Lithic-Mimicry; B = Tiered Interconnected Refugia; C = Vertical Cavities; D = Horizontal Stratification Cavity.

Table 23. Kruskal-Wallis H test comparing biological response metrics by enclosure category (all stations pooled, independent of typology identity)

Metric	H	p-value	Highest median	n
Fish abundance by enclosure level (Enclosed / Semi / Open)	9.90	0.007 *	Open (40)	72
Invertebrate abundance by enclosure level (Enclosed / Semi)	7.11	0.029 *	Enclosed (10)	59

Significance: ** $p < 0.001$; * $p < 0.05$. Surrounding-vicinity (open, $n=12$) zones were excluded from the invertebrate comparison as invertebrate counts were not recorded for this zone type.

4. Discussion

4.1 Enclosure as a design axis affecting fish and invertebrates.

Enclosure degree emerged as a central design variable in this study. Fish abundance was highest in open zones and declined in enclosed ones, while invertebrate abundance showed the reverse; the two groups responded to opposite ends of a single enclosure gradient.

The rapid establishment of resident fauna at Stations A and B supports the refuge dimensioning hypothesis (Hixon and Beets 1993). Both stations offered high spatial heterogeneity and connectivity: Station A through a randomized arrangement of overlapping lithic forms of varied size, and Station B through radially layered, interconnected wall voids. Consistent with the hypothesis that the number, variety, and size of refuges influence the abundance and richness of reef fish, and that fauna reduce predation risk by selecting crevices matching their body size, Station A's irregular sub-lithic crevices supported the widest range of taxa. Station B was occupied across multiple zones, with small schooling fish sheltering in the mid-water tiers and benthic fauna at the structure-seabed interface. Heterogeneity and connectivity thus appear to satisfy the size requirements of several taxa at once, from narrow-crevice benthic species to larger fish, rather than optimizing for a single body-size class.

Station D attracted the highest fish abundance from the earliest weeks yet showed the slowest invertebrate colonization, without a corresponding rise in invertebrate or sessile taxa. Exposure and enclosure therefore operate as a single design axis with opposing outcomes: open, current-exposed geometries favor fish aggregation through attraction, whereas enclosed, refuge-dense geometries favor invertebrate establishment through sheltered settlement.

Occupancy patterns differed by typology: benthic fauna occupied the interstitial voids of Station A; fish occupied the layered walls of Station B; molluscs occupied the internal voids of Station C while fish established between structures; and fish dominated Station D.

4.2 Structural trade-offs and the limits of a single design variable

The marked colonization of Station C's lower voids by invertebrates, including polychaetes, sea urchins, and cowries, despite narrower apertures than the other stations, indicates that crevice geometry directly shapes occupancy. This complicates the expectation that greater enclosure always accelerates colonization: Station C's vertical voids are not enclosed in the manner of the labyrinthine crevices elsewhere, yet they produced the fastest sessile recruitment in the dataset.

Early-stage algae colonized the internal voids of Station C more densely than the external surfaces, and these algae, alongside coral and sessile recruitment at the chimney apertures, in turn attracted grazing sea urchins and polychaetes. Design intent may therefore need to account not only for the shelter requirements of predator-avoidant fauna, but also for food availability and feeding behavior.

Dense early-stage algae were observed within the internal voids of all stations, with occupancy varying by connectivity. Station A's interior crevices held benthic fauna; Station B's ceiling voids supported both fish and benthic fauna; and Station D's ceiling voids, though densely colonized by algae, held only fish and no visible benthic fauna, consistent with their low spatial connectivity. From a design perspective, this raises the question of which structural forms best accelerate the development of biofilm and calcifying algae such as crustose coralline algae (CCA), which release chemical cues that signal settlement suitability to benthic larvae such as coral, barnacles, and molluscs (Hoog Antink et al. 2018; Petersen et al. 2005). A plausible sequence runs from bare substrate, to biofilm and early algal growth, to the recruitment of benthic fauna and herbivorous fish, and finally to a more complex community.

The pattern at Station D, the highest fish abundance alongside the slowest invertebrate colonization, reflects a structural trade-off. Recognizing this trade-off allows designers to avoid a one-size-fits-all approach and adopt target-specific design: complex, complex, high-enclosure structures tailored to rehabilitate coral or invertebrate populations, and open, current-exposed structures intended to augment fish density. It also motivates zonal heterogeneity within a single modular unit, combining enclosed interior crevices for benthic fauna with wider external openings for fish.

4.3 Implications for reef restoration

Because no single structure accommodates all faunal groups, restoration may be more effective when complementary typologies are deployed together, for example pairing Station D with Station A or B, rather than repeating one design. Designing multiple spatial typologies into a single structure is difficult, which makes the deliberate combination of distinct units a practical alternative.

The spacing between structures, or negative space, also affected occupancy yet is commonly overlooked when deployment focuses on the structures alone. The open areas around and between units influenced both fish and benthic fauna, underscoring the value of quantifying spatial pattern at the seascape scale (Harrington et al. 2004), as well as micro-habitat settlement criteria (Wedding et al. 2011). Together with the opposing responses of fish and cryptic invertebrates to enclosure, this indicates that different conservation goals, whether fish aggregation or the recovery of benthic communities, call for deliberately different spatial designs rather than a single generic reef form.

For restoration practice, deploying several reef forms together is more likely to support biodiversity than repeating one form, and placement must account for depth and inter-structural spacing. Future research should test this framework through replicated installations and longer-term monitoring, and extend it toward community-level restoration and the ecosystem-service benefits of recovery, including support for small-scale fisheries and reef-based ecotourism.

5. Limitations

These findings should be read as a proof-of-concept case study rather than a replicated ecological experiment. Each typology was represented by a single unit ($n=1$), which precludes formal statistical replication and means that station-level differences cannot be fully separated from site- or installation-

specific variation; cross-typology comparisons are therefore exploratory, aimed at establishing the feasibility and internal logic of the framework for subsequent replicated testing. The 90-day window captured the migratory-to-resident transition but is short relative to the multi-year timescales of coral growth and sessile community maturation. Trends reported here, particularly coral recruitment density, should be read as early-stage indicators rather than stabilized outcomes.

Finally, all abundance and cover estimates were derived from observer-based assessment of underwater imagery and therefore carry the subjectivity inherent to visual census. Semi-automated annotation tools developed for reef imagery (Pavoni 2022) may improve consistency and reproducibility in future work. Replicated deployments and extended monitoring should test whether the typology-specific patterns identified here persist over longer ecological timescales.

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