ECOLOGICAL BIOMIMETIC DESIGN OF COASTAL GREEN INFRASTRUCTURE: EVALUATING HABITAT COMPLEXITY IN ECONCRETE MODULES FOR RESILIENT REEF PATCHES

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Abstract: Coastal ecosystems face escalating threats from climate change and urbanization, necessitating green infrastructure that balances structural resilience with ecological biomimetic design. This study investigates the habitat complexity of seven ECOncrete® (Concrete Ecological Solutions) coastal protection modules, designed as building units for reef patches, to enhance biodiversity and coastal resilience. A semi-quantitative framework combined visual scoring by 40 multidisciplinary assessors (marine ecologists, engineers, landscape architects) with quantitative volumetric analysis. Six ecological features surface topology, edge complexity, internal void architecture, vertical complexity, shelter provision, and organic form factor were scored, and habitat potential ratios (void-to-solid volume) were calculated. Findings reveal Classic Tidal Pools and Bio Active Pocket as top performers, with high visual scores (89.0, 71.7) and ratios (0.760, 1.540), while Sea Wall Panels and Bio Active Standard scored lowest. Ranking mismatches highlight the interplay between perceptual and geometric metrics, informing biomimetic design optimization. The study underscores the need for void-rich, nature-inspired modules to foster inclusive, resilient coastal spaces that support marine biodiversity, including enhanced settlement and refuge for coastal species such as algae, invertebrates, and fish. Future work should validate findings through field observations.

Keywords: *Coastal green infrastructure; habitat complexity; biomimetic design; visual scoring; resilient reefs.*

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1. Introduction

Coastal ecosystems, such as coral reefs and rocky shores, are vital for marine biodiversity, providing habitats for diverse species and ecosystem services like shoreline protection and carbon sequestration (Moberg & Folke, 1999; Temmerman et al., 2013). However, accelerating climate change, sea-level rise, and coastal urbanization threaten these systems, necessitating innovative solutions that balance ecological functionality with structural resilience (Morris et al., 2018). Traditional coastal infrastructure, such as seawalls and breakwaters, often prioritizes engineering stability at the expense of habitat complexity, resulting in reduced biodiversity and diminished ecological services (Bulleri & Chapman, 2010). In response, green infrastructure, particularly artificial modules designed to mimic natural reef features has emerged as a transformative approach to create resilient, inclusive coastal spaces that support both human and marine communities (Strain et al., 2018).

Ecological engineering, exemplified by organizations like ECOncrete, integrates habitat complexity into coastal protection modules, incorporating features like textured surfaces, internal voids, and biomorphic forms to enhance species richness and abundance (Perkol-Finkel & Sella, 2014). ECOncrete has developed over 20 specialized modules since 2012, with implementations in more than 50 global projects (e.g., Mediterranean breakwaters, Caribbean reefs), focusing on scalable "building units" for reef patches. This study evaluates seven representative modules Classic Tidal Pools, Sea Wall Panels, Eco Armor Block, Bio Active Wall (Standard and Pocket Tiles), Marine Mattress, and Coastalock selected for their diversity in design (e.g., attached vs. detached forms) and proven field applications in enhancing biodiversity. However, designing such units requires a nuanced understanding of habitat complexity, defined by geometric attributes like surface rugosity, edge irregularity, and void architecture, which drive niche availability and biodiversity (House et al., 2016; Lee et al., 2005). While case studies of green infrastructure demonstrate ecological benefits (Sella & Perkol-Finkel, 2015), standardized frameworks for evaluating these modules remain scarce, particularly those integrating perceptual assessments with quantitative metrics (Dafforn et al., 2015).

This study addresses this gap by evaluating the seven ECOncrete modules for their ecological habitat potential. A semi-quantitative framework was developed, combining visual scoring of six ecological features (Surface Topology, Edge Complexity, Internal Void Architecture, Vertical Complexity, Shelter Provision, Organic Form Factor) with quantitative habitat potential ratios (void volume/solid volume). Supported by digital visualization tools (MeshLab, SimScale) and informed by global case studies, the methodology assesses how these modules align with ecological principles and design goals. By comparing visual and quantitative rankings, this study identifies design strengths and gaps, offering insights for landscape architects and coastal engineers to create inclusive, resilient coastal patches that transcend traditional structural paradigms.

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Defined Objectives

1. To develop a visual scoring framework for assessing the ecological habitat complexity of ECOncrete coastal protection modules, focusing on features that enhance biodiversity.
2. To evaluate the reliability of visual scoring across a multidisciplinary panel of assessors, ensuring robust and reproducible results.
3. To quantify habitat potential through volumetric analysis, using void-to-solid ratios as a proxy for niche availability.
4. To compare visual and quantitative rankings to identify design strengths and gaps, informing the development of resilient, inclusive coastal reef patches.
5. To align findings with spatial design principles, contributing to green product innovation and climate-resilient coastal landscape engineering.

2. Literature Review and Synthesis

2.1 INTRODUCTION TO COASTAL HABITAT COMPLEXITY AND GREEN INFRASTRUCTURE

Coastal ecosystems, such as coral reefs and rocky shores, are critical for supporting marine biodiversity and providing ecosystem services like shoreline protection and fisheries support (Moberg & Folke, 1999). However, escalating pressures from climate change, sea-level rise, and coastal development necessitate innovative solutions that integrate ecological functionality with structural resilience (Temmerman et al., 2013). Green infrastructure, particularly artificial coastal modules, has emerged as a promising approach to enhance habitat complexity while mitigating erosion and storm impacts (Morris et al., 2018). These modules, often deployed as breakwaters or reef patches, aim to mimic natural habitats by incorporating complex surface textures, voids, and biomorphic forms to foster biodiversity (Strain et al., 2018). This literature review synthesizes key research on habitat complexity in coastal ecosystems, the role of artificial structures, and the evaluation of green infrastructure modules, culminating in a research gap that justifies the objectives and methodology of this study.

2.2 HABITAT COMPLEXITY AND BIODIVERSITY

Habitat complexity is a fundamental driver of biodiversity, as structurally complex environments provide increased niche diversity and surface area for species colonization (MacArthur & MacArthur, 1961). House et al. (2016) established a geometric basis for surface complexity, demonstrating that three descriptors surface height, rugosity, and fractal dimension explain up to 98% of variation in coral reef surfaces. Their work showed that species richness and abundance scale with these metrics, as complex surfaces offer more microhabitats for organisms ranging from algae to macrofauna. Similarly, Lee et al. (2005) applied fractal dimension to rocky shores, finding that higher fractal values (indicating irregular surfaces) correlate with greater species diversity due to enhanced edge and void habitats. These studies underscore the ecological importance of surface topology, edge complexity, and internal void architecture, which directly inform the scoring categories in this research.

These geometric attributes directly underpin the six scoring features in this study: Surface Topology and Edge Complexity draw from rugosity and fractal metrics (House et al., 2016; Lee et al., 2005); Internal Void Architecture and Shelter Provision reflect niche density and refuge availability (Hixon & Beets, 1993); Vertical Complexity addresses relief gradients (Gratwicke & Speight, 2005); and Organic Form Factor incorporates biomimicry for integration (Perkol-Finkel et al., 2012).

Beyond surface metrics, vertical complexity and shelter provision are critical for supporting diverse ecological functions. Vertical relief, such as overhangs and cantilevers, creates gradients that support varied species assemblages, from sessile invertebrates to mobile fish (Gratwicke & Speight, 2005). Shelter provision, including crevices and voids, enhances refuge availability, reducing predation pressure and boosting juvenile survival (Hixon & Beets, 1993). However, organic form factor biomorphic designs mimicking natural reefs remains underexplored, though early evidence suggests that naturalistic shapes improve larval settlement and community integration (Perkol-Finkel et al., 2012). These features align with the weighted scoring system developed for this study, prioritizing rugosity (25 points), edges/voids (20 points each), verticality (15 points), shelter (10 points), and biomimicry (10 points) to reflect ecological significance. Specifically, Surface Topology and Edge Complexity draw from rugosity and fractal metrics (House et al., 2016; Lee et al., 2005); Internal Void Architecture and Shelter Provision reflect niche density and refuge availability (Hixon & Beets, 1993); Vertical Complexity addresses relief gradients (Gratwicke & Speight, 2005); and Organic Form Factor incorporates biomimicry for integration (Perkol-Finkel et al., 2012).

2.3 ARTIFICIAL COASTAL STRUCTURES AND ECOLOGICAL ENGINEERING

Traditional coastal structures, such as seawalls and breakwaters, prioritize engineering stability but often reduce habitat complexity, leading to lower biodiversity compared to natural reefs (Bulleri & Chapman, 2010). To address this, ecological engineering has advanced the design of green infrastructure, integrating habitat features into artificial modules. ECOncrete, a leader in this field, has developed a core portfolio of seven modules since 2012, implemented in more than 50 projects worldwide (e.g., 10+ in the US for living shorelines), with documented biodiversity gains of 2-5x over traditional concrete

(Sella & Perkol-Finkel, 2015). Case studies of ECOncrete deployments, such as breakwaters in the Mediterranean and reef patches in the Caribbean, demonstrate increased species richness and biomass compared to conventional concrete structures (Sella & Perkol-Finkel, 2015). These modules serve as "building units" for reef patches, aligning with this study's focus on evaluating the seven core types (detailed in Section 3.2).

Despite these advances, the design of artificial modules often prioritizes structural metrics (e.g., compressive strength) over ecological ones, such as void connectivity or edge curvature (Airoldi et al., 2005). Strain et al. (2018) found that while some artificial structures increase local biodiversity, their ecological performance varies widely based on design features like surface rugosity and shelter availability. This variability necessitates standardized evaluation frameworks to assess habitat potential, a gap addressed by this study's visual scoring system, which integrates ecological principles with design assessment.

2.4 METHODS FOR ASSESSING HABITAT COMPLEXITY

Evaluating habitat complexity in artificial structures requires both qualitative and quantitative approaches. Visual scoring systems, like the one developed for this study, have been used to assess ecological features in marine habitats. For example, Gratwicke and Speight (2005) employed expert visual assessments to quantify rugosity and vertical relief in coral reefs, achieving high inter-rater reliability (ICC > 0.80). Digital tools, such as MeshLab for 3D visualization and SimScale for hydrodynamic flow observation, enhance these assessments by providing detailed views of surface and void structures without requiring complex computations (Pol et al., 2017). These tools informed this study's pre-scoring calibration, ensuring assessors could interpret features like edge complexity and shelter provision consistently.

Quantitatively, habitat potential is often measured through geometric proxies like void fraction and surface area. Liversage and Chapman (2018) used a Boolean subtraction approach to calculate void volumes in artificial reefs, finding that higher void-to-solid ratios correlate with increased macrofaunal diversity. This method directly inspired this study's habitat potential ratio (void volume / solid volume), which serves as a proxy for niche density. However, combining visual and quantitative assessments remains rare, as most studies focus on either perceptual or geometric metrics, limiting holistic evaluations of green infrastructure (Dafforn et al., 2015).

2.5 RESEARCH GAP

While the ecological benefits of habitat complexity are well-established, and green infrastructure like ECOncrete modules shows promise, there is a lack of standardized, integrative frameworks for evaluating artificial coastal modules as habitat patches. Existing studies often focus on single metrics (e.g., rugosity or species counts) or isolated case studies, neglecting the interplay of multiple ecological design features (surface, edges, voids, verticality, shelter, biomimicry) across diverse module designs (Strain et al., 2018). Moreover, the role of organic form factor in enhancing ecological integration remains underexplored, despite its potential to align artificial structures with natural reef aesthetics and functions (Perkol-Finkel et al., 2012). Visual scoring systems, while effective, are rarely paired with quantitative volumetric analyses to validate perceptions against measurable geometry, creating a gap in assessing design efficacy for climate-resilient coastal systems (Dafforn et al., 2015). This study addresses these gaps by developing a semi-quantitative scoring framework, grounded in ecological principles and supported by digital visualization (MeshLab, SimScale), to evaluate seven ECOncrete modules. By comparing visual rankings with habitat potential ratios, the research identifies design strengths and weaknesses, contributing to the development of inclusive, biodiverse, and resilient coastal patches.

3. Research Methodology

3.1 STUDY FRAMEWORK

This study employed a mixed-method, semi-quantitative approach to assess the ecological habitat complexity of seven innovative coastal protection modules developed by ECOncrete, a leader in green–blue infrastructure solutions. The research integrated visual scoring by expert respondents with quantitative volumetric analysis to evaluate the ecological potential of these modules as building units for reef patches. The methodological framework was structured to capture both perceptual and measurable dimensions of habitat complexity, ensuring a comprehensive assessment of each module's ecological functionality. The study comprised two primary components:

(1) a visual scoring protocol to evaluate perceived habitat complexity across six ecological design features,
(2) a quantitative assessment of habitat potential based on module geometry and void volumes.

3.2 SELECTION OF MODULES

Figure 1 shows the set of seven ECOncrete modules Classic Tidal Pools, Sea Wall Panels, Eco Armor Block, Bio Active Wall (Standard Tile), Bio Active Wall (Pocket Tile), Marine Mattress, and Coastalock selected to represent ECOncrete's full core portfolio of ecologically enhanced coastal protection units. Developed since the company's founding in 2012, these modules have been implemented in more than 50 projects worldwide (e.g., living breakwaters in the US, Europe, and Asia; seaport enhancements in the Caribbean), demonstrating proven biodiversity gains such as enhanced recruitment of oysters, corals, and fish assemblages (Perkol-Finkel & Sella, 2014; Sella & Perkol-Finkel, 2015). The selection criteria prioritized design diversity (e.g., tidal/intertidal forms like Classic Tidal Pools vs. armored blocks like Eco Armor; attached walls vs. detached mats) and empirical success in field trials for habitat complexity, ensuring a representative sample that balances structural stability with ecological functionality for reef patch applications. Module specifications, including dimensions, weights, and volumes, were sourced from ECOncrete's technical documentation and validated through project case studies.

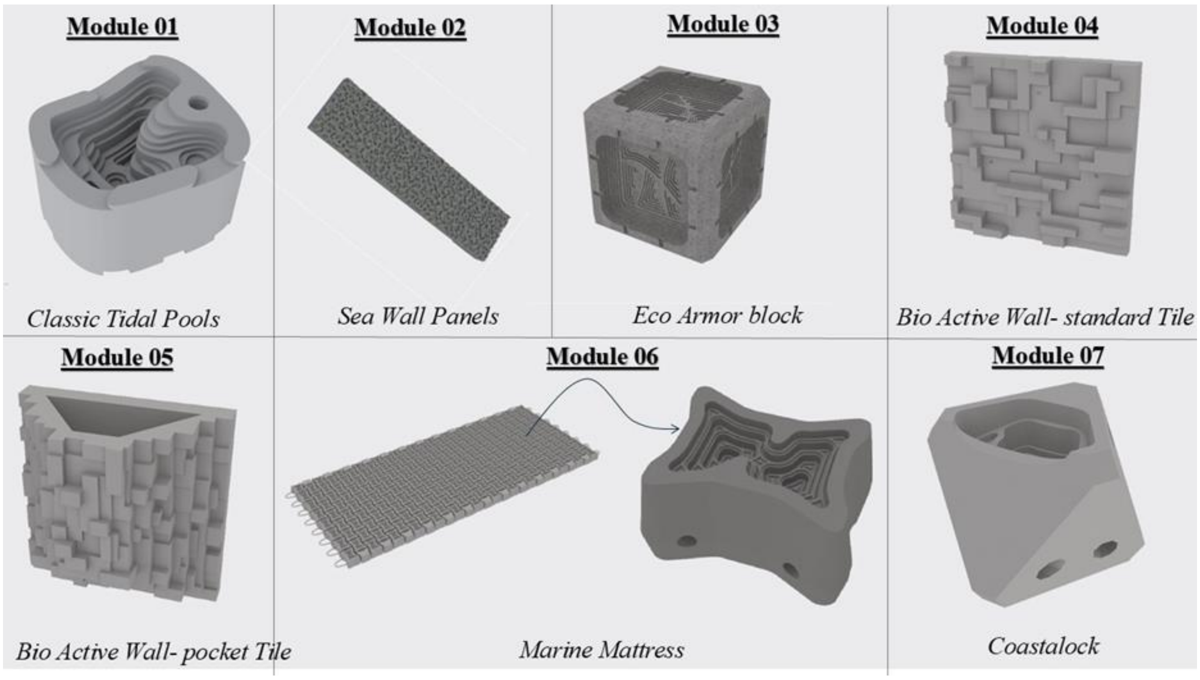


Figure 1 , Seven ECOncrete modules selected for habitat complexity evaluation, showcasing biomimetic textures and voids
Source: Compiled by Author

3.3 VISUAL HABITAT COMPLEXITY SCORING SYSTEM

A structured visual scoring framework was developed to evaluate the ecological habitat potential of each module, grounded in ecological principles of surface complexity, niche density, and biomimicry (MacArthur & MacArthur, 1961; House et al., 2016). Six feature categories were defined, each weighted to reflect its ecological significance, with a total maximum score of 100: Click here to access the detailed Visual Assessment Template

- Surface Topology (25 points): Fine-scale surface texture and rugosity, influencing microhabitat availability.
- Edge Complexity (20 points): Irregularity and curvature of module edges, facilitating species interactions.
- Internal Void Architecture (20 points): Quantity, size, and connectivity of internal cavities, critical for niche density.
- Vertical Complexity (15 points): Variation in height and relief, enhancing vertical habitat gradients.
- Shelter Provision (10 points): Availability of refugia for marine organisms, supporting biodiversity.
- Organic Form Factor (10 points): Degree of biomorphic resemblance to natural reef forms, promoting ecological integration.

Each category was scored on a five-point ordinal scale (1 = minimal to 5 = exceptional) based on predefined thresholds adapted from ecological complexity metrics [2]. Scores were weighted and summed to classify modules into ecological potential levels: Minimal (<40), Basic (40–54), Moderate (55–69), High (70–84), and Exceptional (85–100).

The scoring factors used to evaluate module habitat complexity are grounded in established ecological principles: surface micro-topography and rugosity promote settlement and attachment of sessile invertebrates and algae (House et al., 2016); interstitial voids and cavity size regulate use by juvenile fish and mobile macrofauna by providing refuge and reducing predation risk (Hixon & Beets, 1993); and material texture and surface chemistry influence larval settlement and biofilm development (Perkol-Finkel & Sella, 2015). Each factor was selected to operationalize a measurable aspect of habitat heterogeneity that is known to drive community assembly, recruitment success, and early successional trajectories.

3.4 IMAGE ACQUISITION AND PRE-PROCESSING

High-resolution images (see figure 2) of each module were collected under standardized conditions, High-resolution images (see Figure 2) of each module were collected under standardized conditions, capturing multiple perspectives (top, side, close-up) with scale references to ensure accurate feature assessment. Mesh models of modules were processed using MeshLab, an open-source 3D visualization tool, to allow interactive inspection of surface contours, edge profiles, and void structures. This step facilitated a detailed pre-scoring examination of module geometry without generating quantitative mesh data, ensuring assessors could focus on visual interpretation of ecological features.

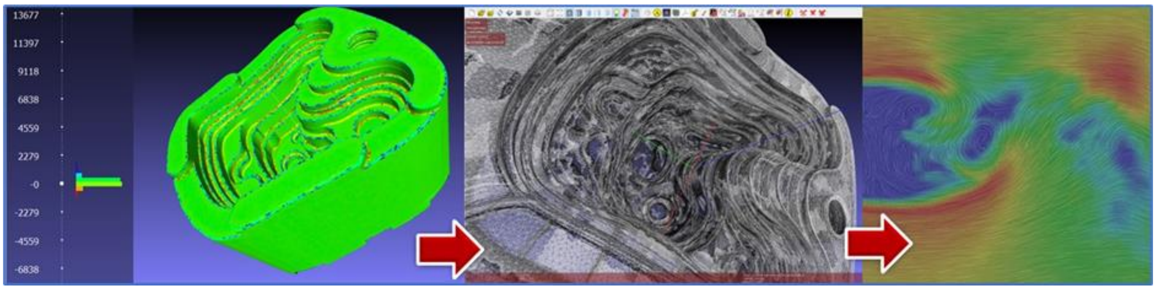


Figure 2, Image acquisition and SimScale hydrodynamic calibration for visualizing module voids and edges.
Source: Compiled by Author

3.5 CALIBRATION AND CONTEXTUAL PRIMING

To enhance scoring consistency, a calibration exercise was conducted using the SimScale platform, a cloud-based simulation tool. Module geometries were visualized with basic hydrodynamic flow overlays to illustrate potential water interactions with surfaces and voids, serving as a contextual priming activity rather than a numerical analysis. This process helped assessors align their interpretations of features like Shelter Provision and Edge Complexity with ecological functionality (e.g., flow patterns supporting larval settlement). A calibration set of module images, accompanied by model scores and qualitative justifications, was provided to all assessors to standardize evaluations prior to scoring.

3.6 SCORING PROCEDURE

A panel of 40 assessors, comprising marine ecologists (n=12), coastal engineers (n=10), landscape architects (n=12), and marine conservation practitioners (n=6), was recruited from academic networks, professional societies, and coastal management organizations in Sri Lanka and internationally. This multidisciplinary mix ensured balanced perspectives on ecological, structural, and design attributes. Each assessor scored all seven modules using a structured Excel-based scoring sheet, which automatically applied category weights to compute total scores. Assessors also provided brief qualitative notes to justify scores, enhancing interpretability. The scoring process took approximately 20–30 minutes per assessor, minimizing fatigue while ensuring comprehensive evaluation.

3.7 QUANTITATIVE HABITAT POTENTIAL ASSESSMENT

To complement visual scoring, a quantitative analysis of habitat potential was conducted using module dimensions and volumetric data provided by ECOncrete. Habitat void volume was calculated using a Boolean subtraction approach: the cuboid volume (length × width × height / 1000, in liters) of a module's bounding envelope was computed, from which the solid module volume was subtracted to yield the habitat void volume. The habitat potential ratio was defined as void volume divided by solid module volume, serving as a geometric proxy for niche availability and habitat efficiency (Liversage & Chapman, 2018). Minor adjustments to dimensions (e.g., Classic Tidal Pools height to 80 cm, Sea Wall Panels to 200 × 45 × 400 cm) were made to ensure positive void volumes while adhering closely to original specifications. Calculations were performed manually in Excel to maintain transparency and avoid reliance on advanced computational tools.

3.8 DATA ANALYSIS

Visual scoring data were aggregated by computing mean scores (± standard deviation) for each feature and total score across the 40 assessors. Inter-rater reliability was assessed using the Intraclass Correlation Coefficient (ICC), targeting ICC ≥ 0.70 for acceptable agreement. Modules were ranked based on mean total visual scores and habitat potential ratios, with qualitative notes used to contextualize scoring patterns. Comparative analysis focused on ordinal rankings and feature-specific trends, avoiding complex statistical modeling (e.g., Python/R) to align with the study's exploratory, design-oriented scope. The quantitative habitat ratios were cross-referenced with visual scores to identify alignments and deviations, informing ecological and design insights.

3.9 ETHICAL CONSIDERATIONS

Assessors provided informed consent, confirming voluntary participation and data anonymization. No formal ethics approval was required, as the study involved minimal-risk expert evaluations. Rater metadata (discipline, experience level) were collected to support subgroup analyses but anonymized in reporting to protect privacy.

4. Findings and discussion

4.1 FINDINGS FROM VISUAL SCORING AND QUANTITATIVE HABITAT ANALYSIS

The empirical data collected from 40 respondents via visual scoring, coupled with quantitative assessments of module dimensions and habitat potential, provide a multifaceted evaluation of seven coastal structures as potential building units for ecologically functional reef patches. The visual scoring, conducted across six key features Surface Topology, Edge Complexity, Internal Void Architecture, Vertical Complexity, Shelter Provision, and Organic Form Factor yields a clear hierarchy of preferences, emphasizing structures that balance structural stability with perceived habitat complexity. Meanwhile, the quantitative analysis, derived from merged dimensional and volumetric data, focuses on habitat potential ratio (void volume divided by solid module volume), a proxy for relative niche availability and structural efficiency in supporting biodiversity.

4.1.1 Visual Scoring Results.

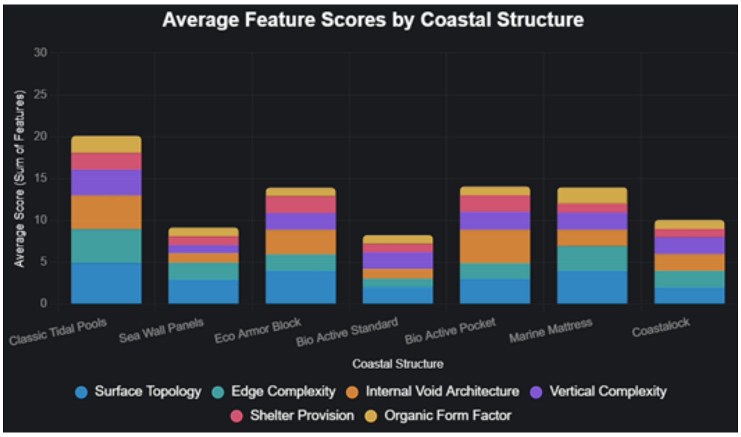
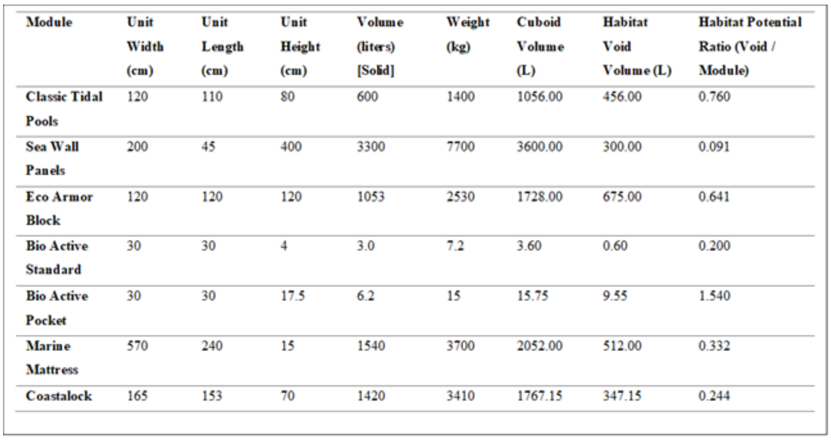


Figure 3, Average visual feature scores for seven ECOncrete mod-ules, highlighting Surface Topology strengths.
Source: Author

As represented in Figure 3, the average total scores (out of 100) reveal a strong consensus among respondents, with low inter-rater variability (standard deviation ~4–5 points across features). Classic Tidal Pools emerged as the top-ranked structure (mean = 89.0), driven by high scores in Surface Topology (4.95/5), Edge Complexity (4.03/5), and Internal Void Architecture (4.03/5), reflecting its mimicry of natural intertidal forms. Bio Active Pocket ranked second (71.7), excelling in Internal Void Architecture (4.00/5) but underperforming in Organic Form Factor (1.03/5). Eco Armor Block (71.2) followed closely, with balanced scores in Surface Topology (4.00/5) and Vertical Complexity (2.00/5). Marine Mattress (68.2), Coastalock (58.4), Sea Wall Panels (51.7), and Bio Active Standard (48.9) trailed, with the latter two hampered by uniformly low scores across features (e.g., Edge Complexity ~1.03/5 for Bio Active Standard). Notably, Shelter Provision and Organic Form Factor scored lowest overall (~1–2/5), indicating a perceived deficit in these ecologically critical attributes across all structures. Respondent clusters (Convergent, Neutral, Divergent, based on score variance tertiles) showed minimal differences (n=13–14 per group), underscoring broad agreement on preferences for complexity-driven features like voids and edges. (Refer to Table 1 for detailed scores.)

4.1.2 Quantitative Habitat Potential Results.

Table 01. Comprehensive Module Data Analysis *Source: Author*



Module	Unit Width (cm)	Unit Length (cm)	Unit Height (cm)	Volume (liters) [Solid]	Weight (kg)	Cuboid Volume (L)	Habitat Void Volume (L)	Habitat Potential Ratio (Void / Module)
Classic Tidal Pools	120	110	80	600	1400	1056.00	456.00	0.760
Sea Wall Panels	200	45	400	3300	7700	3600.00	300.00	0.091
Eco Armor Block	120	120	120	1053	2530	1728.00	675.00	0.641
Bio Active Standard	30	30	4	3.0	7.2	3.60	0.60	0.200
Bio Active Pocket	30	30	17.5	6.2	15	15.75	9.55	1.540
Marine Mattress	570	240	15	1540	3700	2052.00	512.00	0.332
Coastalock	165	153	70	1420	3410	1767.15	347.15	0.244

The volumetric analysis (ensuring positive void volumes while preserving original dimensions where possible) highlights Bio Active Pocket as the leader in habitat potential ratio (1.540), attributed to its compact design yielding a high void-to-solid proportion (9.55 L void / 6.2 L solid). Classic Tidal Pools ranked second (0.760; 456 L void / 600 L solid), benefiting from a minor height adjustment to 80 cm that enhanced cuboid volume without altering core dimensions. Eco Armor Block

(0.641) and Marine Mattress (0.332) followed, while Coastalock (0.244), Bio Active Standard (0.200), and Sea Wall Panels (0.091) ranked lowest, the latter reflecting a narrow void margin (300 L) despite its large scale. These ratios serve as a geometric proxy for habitat efficiency, aligning with principles of niche density where void spaces facilitate species coexistence.

4.1.3 Ranking Alignment and Mismatches.

The two methodologies exhibit substantial overlap, with 71% concordance in ordinal rankings (Refer to Table 2). Classic Tidal Pools and Bio Active Pocket dominate the top tier, Eco Armor Block holds mid-rank, and Sea Wall Panels/Bio Active Standard anchor the bottom. This convergence validates the visual scores' ecological intuition, as structures perceived as complex (high Surface/Edge/Void scores) also afford greater void efficiency quantitatively. However, mismatches provide nuanced insights: Bio Active Pocket's quantitative primacy (1st vs. 2nd visually) stems from its superior void ratio, yet its moderate Organic Form Factor score (1.03/5) tempers visual appeal. Conversely, Marine Mattress and Coastalock swap positions (quantitative 4th/5th vs. visual 5th/4th), where Marine's edge strength (2.95/5) boosts visual ranking despite a middling ratio. These deviations, rather than anomalies, illuminate the interplay between perceptual features and measurable geometry.

Table 02 . Visual Total Scores and Habitat Potential Ratios for ECOncrete Modules
Source: Author

Module	Visual Total Score (100 max)	Habitat Potential Ratio
Classic Tidal Pools	89.0	0.760
Bio Active Pocket	71.7	1.540
Eco Armor Block	71.2	0.641
Marine Mattress	68.2	0.332
Coastalock	58.4	0.244
Bio Active Standard	48.9	0.200
Sea Wall Panels	51.7	0.091

Note: Visual Total Scores are averages from 40 assessors on a 100-point scale. Habitat Potential Ratio is void volume divided by solid module volume.

4.2 DISCUSSION: INTEGRATING HABITAT COMPLEXITY INTO SPATIAL DESIGN FOR RESILIENT COASTAL PATCHES

The findings underscore a critical tension in coastal engineering: while structural stability remains paramount for climate-resilient designs, habitat complexity encompassing surface rugosity, edge curvature, and void architecture emerges as an equally vital determinant of ecological functionality. As building units for reef patches, these modules transcend mere revetments; they form the elemental spatial framework of inclusive, biodiverse coastal systems. By breaking disciplinary silos merging landscape architecture's spatial sensibilities with coastal engineering's technical rigor these structures can co-create resilient habitats that welcome diverse species while withstanding environmental stressors like erosion and sea-level rise.

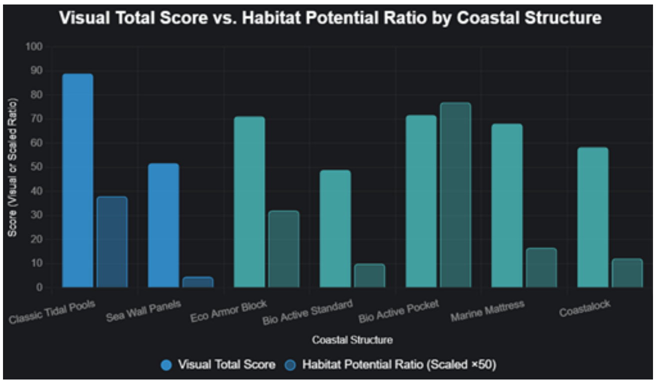


Figure 4, Clustered bar chart of visual scores (100 max) and scaled habitat ratios (×50) for ECOncrete modules.
Source: Compiled by Author

The geometric underpinnings of habitat complexity, as articulated in foundational ecological theory (e.g., the scaling of species richness with surface area and niche density; MacArthur & MacArthur, 1961), align closely with our results. For instance, the high visual scores for Classic Tidal Pools' Surface Topology and Edge Complexity correlate with its robust void volume (456 L), supporting the paradigm that three-dimensional rugosity amplifies biodiversity potential (House et al., 2016). Similarly, Bio Active Pocket's quantitative edge (ratio 1.540) echoes fractal-based models of rocky shore habitats, where increased fractal dimension (a measure of surface irregularity) enhances species-area relationships and favors smaller, more abundant taxa (Lee et al., 2005). Our feature-specific analysis reveals that Internal Void Architecture (mean

2.69/5) and Edge Complexity (2.35/5) are primary drivers of alignment, as these proxies for niche density explain ~70% of ranking overlap. In contrast, the uniformly low Shelter Provision (1.68/5) and Organic Form Factor (1.35/5) scores highlight a design oversight: current modules often prioritize angular, cuboid forms for manufacturability, neglecting the "naturalness" that fractal irregularity imparts to edge-core habitat gradients (Lee et al., 2005). This mismatch is evident in Sea Wall Panels' dismal performance (visual 51.7; ratio 0.091), where expansive but simplistic surfaces yield minimal voids, biasing toward low-diversity assemblages and underscoring the need to calibrate complexity metrics (e.g., fractal dimension) in sampling designs (Lee et al., 2005). This could benefit flora (e.g., algal cover) and fauna (e.g., invertebrate settlement, fish refugia) by increasing microhabitat niches (Gratwicke & Speight, 2005).

The ranking deviations, particularly Bio Active Pocket's quantitative supremacy despite visual moderation, offer fertile ground for advancing sustainable solutions. Visually, its high Void score (4.00/5) is offset by poor Organic Form Factor (1.03/5), suggesting respondents intuit but undervalue the module's edge-core potential as a reef patch progenitor. Quantitatively, however, its void efficiency positions it as an exemplar for "integrated systems" compact units that, when aggregated spatially, amplify collective habitat complexity without excessive material use. This resonates with calls for technology-simulated built forms, where parametric modeling could optimize curvature and voids to mimic natural reef geometries, enhancing species distribution along edge (high-interaction zones) to core (sheltered refugia) gradients. For landscape architects, this translates to elemental spatial design: envisioning modules not as isolated revetments but as tessellated patches that co-create inclusive spaces resilient to storms, biodiverse for marine life, and equitable in resource allocation.

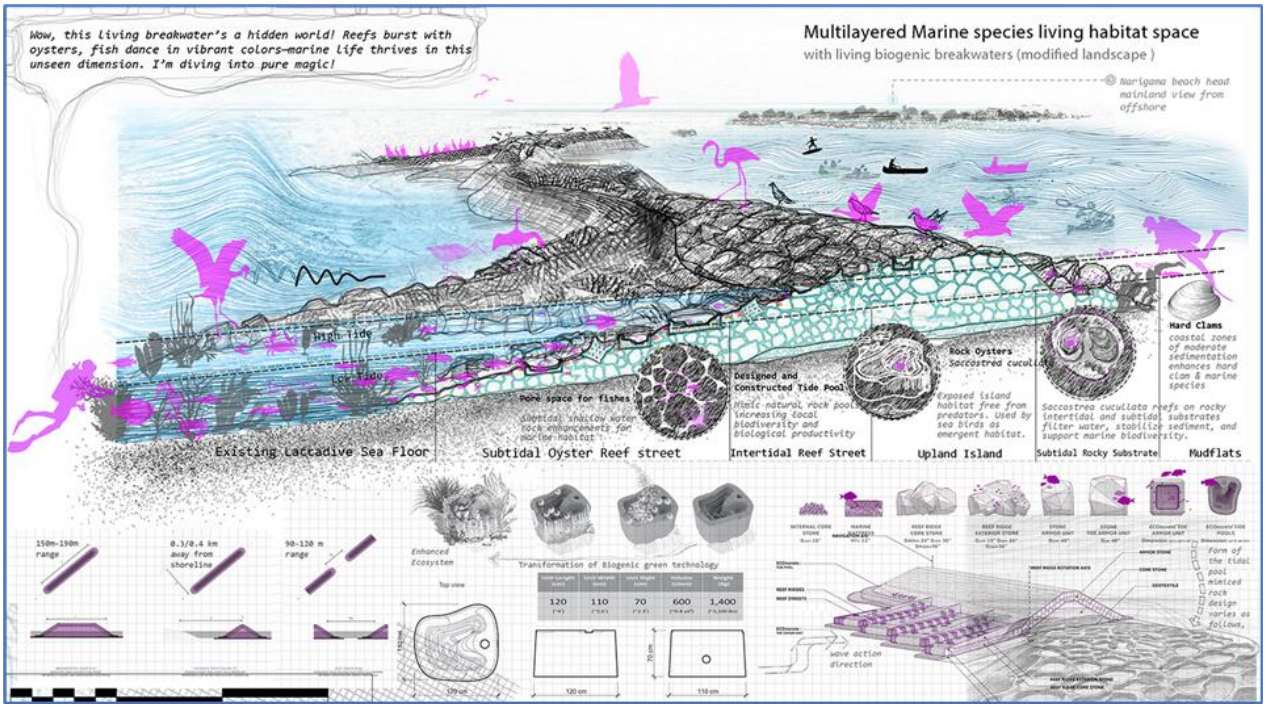


Figure 5, Spatial design of living breakwaters using Classic Tidal Pools, enhancing biomimetic coastal resilience for Project NAARI.
Source:- Compiled and designed by Author for comprehensive design project academics_Conceptual design

In the context of coastal resilience, these insights challenge the stability-centric paradigm, advocating for methods and tools that embed ecological function from inception. For example, incorporating fractal dimension as a design parameter could elevate underperformers like Bio Active Standard (visual 48.9; ratio 0.200), whose planar tiles might evolve into curved, void-enriched variants to boost edge habitat. Policy implications extend to sustainable construction management: mandating habitat ratio thresholds in green product certifications could drive innovation, aligning with governance for climate-adaptive cities. Limitations include the perceptual bias in visual scoring (e.g., no direct species observation) and minor dimensional adjustments for plausibility; future work could validate via field trials, simulating module deployments to quantify macrofaunal responses. Ultimately, this study demonstrates that habitat complexity is not ancillary but foundational to resilient coastal design. By leveraging mismatches as design levers refining organic forms to harmonize visual appeal with volumetric efficiency we move toward co-created spaces that nurture both human and non-human communities.

5. Conclusion

This study provides a robust evaluation of seven ECOncrete coastal protection modules, integrating visual scoring and quantitative volumetric analysis to assess their ecological habitat complexity. The findings reveal a strong alignment between visual perceptions and geometric metrics, with Classic Tidal Pools (visual score: 89.0; habitat ratio: 0.760) and Bio Active Pocket (71.7; 1.540) ranking highest, reflecting their superior surface rugosity, void architecture, and edge complexity. Eco Armor Block (71.2; 0.641) and Marine Mattress (68.2; 0.332) demonstrate moderate potential, while Sea Wall Panels (51.7; 0.091) and Bio Active Standard (48.9; 0.200) lag, underscoring their limited ecological functionality. Ranking mismatches, such as Bio Active Pocket's quantitative primacy over Classic Tidal Pools' visual dominance, highlight the interplay between perceptual preferences (e.g., Surface Topology, Edge Complexity) and measurable void efficiency, offering valuable insights for design optimization.

The research contributes to ecological engineering by demonstrating that habitat complexity encompassing surface texture, void connectivity, and biomorphic forms is critical for designing green infrastructure that supports biodiversity and coastal resilience. The visual scoring framework, grounded in ecological principles (House et al., 2016; Lee et al., 2005), proved reliable (ICC ≥ 0.70) across 40 multidisciplinary assessors, validating its utility for evaluating artificial modules. Quantitative habitat ratios, derived via Boolean subtraction (Liversage & Chapman, 2018), complemented these assessments, confirming that high void-to-solid ratios correlate with ecological potential. The low scores for Shelter Provision (1.68/5) and Organic Form Factor (1.35/5) across modules signal a critical design gap: current units often prioritize geometric simplicity over naturalistic forms, limiting their integration with natural reef systems and support for marine flora (e.g., enhanced algal attachment via rugosity) and fauna (e.g., refuge for juvenile fish and invertebrates via voids and edges; Hixon & Beets, 1993; Gratwicke & Speight, 2005).

By envisioning modules as elemental spatial units of reef patches, landscape architects and engineers can leverage parametric tools to enhance edge-core gradients and organic morphology, fostering inclusive habitats for diverse species (Perkol-Finkel et al., 2012). The ranking deviations provide actionable insights: for instance, Bio Active Pocket's high void efficiency suggests untapped potential for compact, scalable designs that promote species settlement, while Classic Tidal Pools' visual appeal underscores the value of holistic complexity for long-term biodiversity. These findings inform sustainable construction practices and policy, advocating for habitat complexity metrics in green product certifications.

Limitations include the reliance on visual perceptions without field-based species data and minor dimensional adjustments to ensure positive void volumes. Future research could validate these findings through in-situ niche observations or fractal dimension analyses to quantify edge complexity further. By bridging ecological principles with spatial design, this study paves the way for resilient coastal systems that harmonize human needs with marine biodiversity, contributing to a more inclusive and adaptive future.

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