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

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Abstract: Coastal ecosystems face escalating threats from climate change and urbanisation, necessitating green infrastructure that balances structural resilience with ecological biomimetic design. This study investigates the habitat complexity of seven ECOncrete® coastal protection modules designed as building units for reef patches to evaluate their potential to enhance biodiversity and coastal resilience. A semi-quantitative framework integrated visual scoring by a multidisciplinary expert panel with quantitative volumetric analysis across six ecological features: surface topology, edge complexity, internal void architecture, vertical complexity, shelter provision, and organic form factor. Habitat potential ratios (void-to-solid volume) were calculated as geometric proxies for niche availability. Classic Tidal Pools and Bio Active Pocket emerged as top performers with visual scores of 89.0 and 71.7 and habitat ratios of 0.760 and 1.540, while Sea Wall Panels and Bio Active Standard scored lowest. Resilient intelligence — defined as the integration of expert perceptual judgement with exploratory computational sensitivity analysis — was incorporated through Random Forest modelling, identifying Surface Topology and Edge Complexity as dominant design attributes. Ranking mismatches highlight the complementary nature of perceptual and geometric metrics. The study underscores the potential of void-rich, nature-inspired modules to support marine biodiversity, with field validation recommended as a necessary next step.

Keywords: *Adaptive reef patches; Biomimetic design; Coastal green infrastructure; Habitat complexity; Resilient intelligence; Visual scoring.*

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 bio-morphic 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 Pro-vision, 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.

This study introduces the concept of resilient intelligence as an evaluative orientation that integrates human perceptual judgement with computational sensitivity analysis to inform biomimetic design decisions in coastal green infrastructure. Distinct from resilience which describes a system's capacity to absorb disturbance and reorganise (Holling, 1973) and from adaptive capacity, which refers to the ability of a system to adjust to change (Folke et al., 2010), resilient intelligence operates at the *design decision* level: it describes the deliberate combination of expert perceptual assessment and feature-importance analysis to identify which habitat attributes most effectively drive ecological potential in artificial structures. In this study, resilient intelligence is operationalised in two steps: first, through structured visual scoring by a multidisciplinary expert panel that encodes design knowledge about ecological complexity; and second, through exploratory Random Forest feature-importance analysis that reveals which of the scored attributes most strongly predicts habitat potential ratios. Together, these two layers move the evaluation beyond descriptive ranking toward actionable design guidance making the framework not merely analytical, but generative for future module refinement.

Defined Objectives

1. To develop a visual scoring framework for assessing the ecological habitat complexity of ECOn-crete 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 Theoretical Context

2.1 COASTAL HABITAT COMPLEXITY AND BIODIVERSITY

Habitat complexity is a foundational driver of marine biodiversity, as structurally varied environments provide greater niche diversity, surface area, and microhabitat availability for species colonisation (MacArthur & MacArthur, 1961). House et al. (2016) established a geometric basis for surface complexity in coral reef systems, demonstrating that three descriptors surface height, rugosity, and fractal dimension collectively explain up to 98% of variation in reef surface form, and that species richness scales directly with these metrics. Lee et al. (2005) extended this framework to rocky shores, finding that higher fractal dimension values correlate with greater species diversity through enhanced edge and void habitats. Together, these studies provide the ecological rationale for the six scoring features used in this study: Surface Topology and Edge Complexity draw from rugosity and fractal metrics; Internal Void Architecture and Shelter Provision reflect niche density and refuge availability (Hixon & Beets, 1993); Vertical Complexity addresses relief gradients that support varied species assemblages from sessile invertebrates to mobile fish (Gratwicke & Speight, 2005); and Organic Form Factor captures biomorphic resemblance to natural reefs, which early evidence suggests improves larval settlement and community integration (Perkol-Finkel et al., 2012).

2.2 ARTIFICIAL COASTAL STRUCTURES AND ECOLOGICAL ENGINEERING.

Traditional coastal infrastructure seawalls, breakwaters, and revetments priorities structural stability at the expense of habitat complexity, typically yielding lower biodiversity than natural reefs (Bulleri & Chapman, 2010; Airoldi et al., 2005). Ecological engineering addresses this by designing artificial modules that integrate habitat-forming features into protective structures. ECOncrete has been a leading practitioner of this approach since 2012, developing a portfolio of ecologically enhanced modules deployed in over 50 projects worldwide, with documented biodiversity gains of two to five times those of conventional concrete in comparable settings (Sella & Perkol-Finkel, 2015). However, Strain et al. (2018) found that ecological performance varies considerably across artificial structure designs, depending on the specific configuration of surface rugosity, shelter availability, and void architecture underscoring the need for standardised evaluative frameworks rather than case-by-case assessment.

2.3 METHODS FOR ASSESSING HABITAT COMPLEXITY IN ARTIFICIAL MODULES

Two broad methodological approaches have been used to evaluate habitat complexity in artificial coastal structures. Qualitatively, visual scoring systems have been employed to assess ecological features in marine habitats: Gratwicke and Speight (2005) demonstrated that expert visual assessment of rugosity and vertical relief can achieve strong inter-rater agreement, supporting the use of structured perceptual scoring as a valid proxy for ecological measurement. Digital visualisation tools such as MeshLab and SimScale further support this by enabling detailed inspection of surface contours, edge profiles, and void geometries prior to scoring (Pol et al., 2017). Quantitatively, geometric proxies such as void fraction and surface area have been used to measure habitat potential; Liversage and Chapman (2018) applied a Boolean subtraction approach to calculate void volumes in artificial reef structures, finding that higher void-to-solid ratios correlate with increased macrofaunal diversity. This method directly informs the habitat potential ratio used in the present study. Despite the complementary strengths of perceptual and geometric approaches, they are rarely integrated within a single evaluative framework (Dafforn et al., 2015) a gap this study directly addresses.

2.4 RESEARCH GAP AND THEORETICAL POSITIONING

Existing literature on artificial coastal modules tends to focus either on single metrics (rugosity, species counts) or on isolated case studies of specific deployments, without integrating multiple ecological design features across a comparative module set (Strain et al., 2018). The role of organic form factor in ecological performance remains particularly underexplored, despite its theoretical relevance to larval settlement and habitat integration (Perkol-Finkel et al., 2012). Furthermore, the concept of resilient intelligence as defined in this study, the deliberate integration of expert perceptual judgement with computational sensitivity analysis to guide biomimetic design has not previously been applied as an evaluative lens in coastal green infrastructure assessment. This study addresses these gaps by developing a semi-quantitative framework that combines structured visual scoring with volumetric habitat analysis and exploratory feature-importance modelling across seven ECOncrete modules.

3. Research Methodology

This section outlines the mixed-method approach adopted to evaluate habitat complexity in the selected ECOncrete modules, integrating visual expert assessment, volumetric analysis, and exploratory feature-importance modelling.

3.1 STUDY FRAMEWORK

This study employed a semi-quantitative, mixed-method approach to assess the ecological habitat complexity of seven ECOncrete coastal protection modules. The framework was structured around two complementary components:

(1) a structured visual scoring protocol evaluating perceived habitat complexity across six ecological design features, and

(2) a quantitative assessment of habitat potential derived from module geometry and void volumes.

An exploratory feature-importance analysis using Random Forest modelling was subsequently applied as a third layer, consistent with the resilient intelligence perspective introduced in Section 1. Together, these components capture both perceptual and measurable dimensions of habitat complexity, enabling a comparative assessment of each module's ecological functionality as a building unit for reef patches.

3.2 SELECTION OF MODULES

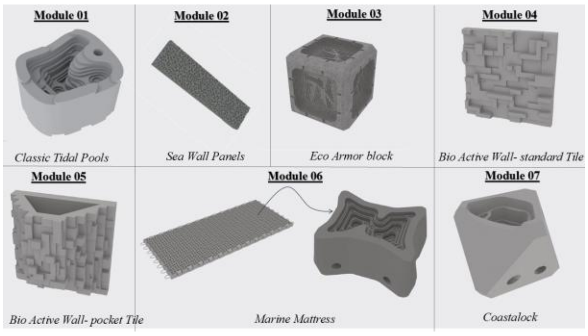


Figure 1: Seven ECOncrete modules selected for habitat complexity evaluation, showcasing biomimetic textures and voids
(Source: Compiled by Author)

Seven ECOncrete modules were selected to represent the full core portfolio of the company's ecologically enhanced coastal protection units (Figure 1): Classic Tidal Pools, Sea Wall Panels, Eco Armor Block, Bio Active Wall (Standard Tile), Bio Active Wall (Pocket Tile), Marine Mattress, and Coastalock. Developed since ECOncrete's founding in 2012 and implemented in more than 50 projects worldwide including living breakwaters in the US, Europe, and Asia, and seaport enhancements in the Caribbean. These modules have demonstrated biodiversity gains including enhanced recruitment of oysters, corals, and fish assemblages in documented field deployments (Perkol-Finkel & Sella, 2014; Sella & Perkol-Finkel, 2015). Selection criteria prioritised design diversity, contrasting tidal and intertidal forms, attached wall types, and detached mat configurations, to ensure a representative sample balancing structural stability with ecological functionality. Module specifications, including dimensions, weights, and volumes, were sourced from ECOncrete's technical documentation.

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:

- Surface Topology (25 points): fine-scale surface texture and rugosity, influencing microhabitat availability and settlement substrate.
- Edge Complexity (20 points): irregularity and curvature of module edges, facilitating species interactions and attachment.

- Internal Void Architecture (20 points): quantity, size, and connectivity of internal cavities, critical for niche density and refuge.
- Vertical Complexity (15 points): variation in height and relief, supporting vertical habitat gradients and species assemblage diversity.
- Shelter Provision (10 points): availability of refugia for marine organisms, supporting juvenile fish and invertebrate survival (Hixon & Beets, 1993).
- Organic Form Factor (10 points): degree of biomorphic resemblance to natural reef forms, promoting larval settlement and ecological integration (Perkol-Finkel et al., 2012).

Each category was scored on a five-point ordinal scale (1 = minimal to 5 = exceptional) based on predefined thresholds adapted from established ecological complexity metrics (House et al., 2016; Lee et al., 2005). Total weighted scores classified modules into five ecological potential levels: Minimal (<40), Basic (40–54), Moderate (55–69), High (70–84), and Exceptional (85–100). Weightings were assigned in proportion to the ecological significance of each attribute as documented in the literature, with surface rugosity receiving the highest weighting (25 points) given its established role as the primary predictor of species richness and abundance.

3.4 IMAGE ACQUISITION AND PRE-PROCESSING

High-resolution images of each module were collected under standardised conditions, capturing multiple perspectives top, side, and close-up with scale references to support accurate feature assessment (Figure 2). Mesh models were processed using MeshLab, an open-source 3D visualisation tool, enabling interactive inspection of surface contours, edge profiles, and void structures. This pre-scoring examination of module geometry ensured assessors could focus on visual interpretation of ecological features without requiring quantitative mesh outputs.

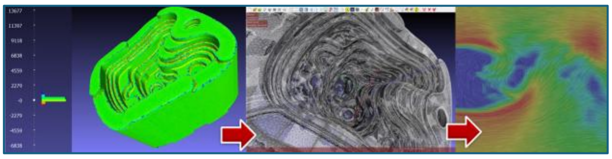


Figure 2: Image acquisition and SimScale hydrodynamic calibration for visualizing module voids and edges. (Source: Compiled by Author)

3.5 CALIBRATION AND CONTEXTUAL PRIMING

To promote scoring consistency, a calibration exercise was conducted prior to the scoring procedure. Module geometries were visualised using the SimScale platform, a cloud-based simulation tool, with basic hydrodynamic flow overlays illustrating potential water interactions with surfaces and voids. This served as a contextual priming activity not a numerical analysis, helping assessors align their interpretations of features such as Shelter Provision and Edge Complexity with ecological functionality. A calibration set of module images, accompanied by example scores and qualitative justifications, was distributed to all assessors before scoring commenced. It should be noted that the priming process involved exposure to SimScale flow visualisations prior to scoring, which may have introduced a degree of perceptual anchoring; this is acknowledged as a limitation in Section 5.

3.6 SCORING PROCEDURE

A pilot expert panel comprising professionals from marine ecology, coastal engineering, landscape architecture, and marine conservation practice was recruited through academic networks and professional associations in Sri Lanka and internationally. This multidisciplinary composition ensured that ecological, structural, and design perspectives were represented in the scoring outcomes. Each assessor evaluated all seven modules using a structured Excel-based scoring sheet that automatically applied category weights to compute total scores. Assessors also provided brief qualitative notes to contextualise their scores and aid interpretability. The scoring process was estimated at 20–30 minutes per assessor. Given the pilot nature of this study, the panel size represents a convenience sample appropriate for an exploratory framework; larger-scale validation with a formally recruited and stratified panel is recommended as a priority for future research.

3.7 QUANTITATIVE HABITAT POTENTIAL ASSESSMENT

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

Figure 3:. Comprehensive module data analysis (Source: Author)

Quantitative habitat potential was assessed using module dimensions and volumetric data sourced from ECOncrete's technical documentation. Habitat void volume was calculated using a Boolean subtraction approach: the cuboid bounding volume (length × width × height, converted to litres) was computed for each module, and the manufacturer-specified solid volume was subtracted to yield the estimated 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, consistent with the approach of Liversage and Chapman (2018). Minor dimensional adjustments were made for two modules

Classic Tidal Pools (height adjusted to 80 cm) and Sea Wall Panels (adjusted to 200 × 45 × 400 cm) to resolve negative void values arising from specification ambiguities. These adjustments were kept as close to original specifications as possible, and the resulting ratios should be interpreted as indicative proxies rather than precise volumetric measurements. Calculations were performed manually in Excel to maintain full transparency.

3.8 DATA ANALYSIS

Visual scoring data were aggregated by computing mean scores and standard deviations for each feature and total score across the assessor panel. Low inter-rater variability indicated by standard deviations of approximately 4–5 points across features suggested broad agreement among assessors on module rankings and feature assessments. Formal inter-rater reliability testing using intraclass correlation analysis is recommended for future studies employing larger, more formally stratified panels. Modules were ranked by mean total visual score and by habitat potential ratio, and comparative analysis focused on ordinal rankings and feature-specific trends. Quantitative habitat ratios were cross-referenced with visual scores to identify alignments and deviations, informing ecological and design insights.

3.9 EXPLORATORY FEATURE-IMPORTANCE ANALYSIS

To incorporate the resilient intelligence layer described in Section 1, an exploratory feature-importance analysis was conducted using a Random Forest model fitted to the aggregated scoring dataset. Given the small number of modules evaluated (n = 7), this analysis is explicitly framed as an exploratory sensitivity analysis rather than a predictive machine learning exercise. No training–testing split was applied, and results should be interpreted as indicative of relative feature influence within this dataset only, not as generalisable predictive relationships. The analysis was conducted to identify which ecological design features most strongly co-vary with habitat potential ratios, offering preliminary guidance for biomimetic design prioritisation. Results are presented in Section 4.1.4.

3.10 ETHICAL CONSIDERATIONS

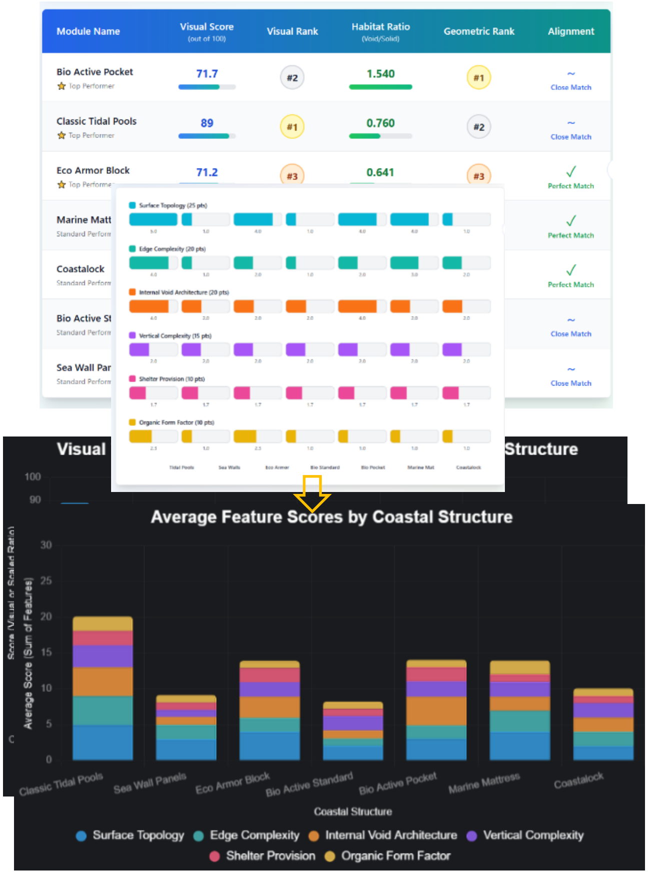
All assessors participated voluntarily and provided informed consent confirming data anonymisation. No formal ethics approval was required, as the study involved minimal-risk expert evaluation of module images. Assessor metadata including disciplinary background and experience level were collected to contextualise scoring patterns but are reported only in aggregate to protect participant privacy.

4. Findings and Discussion

4.1 VISUAL SCORING RESULTS

Visual scoring across six ecological features yielded a clear performance hierarchy among the seven modules, with low inter-rater variability (standard deviation approximately 4–5 points across features), indicating broad consensus within the expert panel. Classic Tidal Pools emerged as the top-ranked module (mean total score = 89.0 out of 100), driven by exceptional Surface Topology (4.95/5), strong Edge Complexity (4.03/5), and high Internal Void Architecture (4.03/5), reflecting its close mimicry of natural intertidal pool forms. Bio Active Pocket ranked second (71.7), excelling in Internal Void Architecture (4.00/5) but scoring low on Organic Form Factor (1.03/5). Eco Armor Block (71.2) followed with balanced performance across 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) ranked progressively lower, with the latter two constrained by uniformly low scores across most features (refer to Figure 3 for detailed scores).

Notably, Shelter Provision (mean 1.68/5) and Organic Form Factor (mean 1.35/5) scored lowest across all seven modules, indicating a consistent perceived deficit in these ecologically critical attributes. This pattern suggests that current ECOncrete module designs, while strong in surface



(Source: Compiled by Author)

Figure 4: Mean visual feature scores for seven ECOncrete modules across six ecological attributes.
(Source: Author)

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would maximise their integration with natural reef communities.

4.2 QUANTITATIVE HABITAT POTENTIAL RESULTS

Volumetric analysis identified Bio Active Pocket as the leader in habitat potential ratio (1.540), a result of its compact geometry producing a high void-to-solid proportion (9.55 L void / 6.2 L solid). Classic Tidal Pools ranked second (ratio 0.760; 456 L void / 600 L solid). Eco Armor Block (0.641) and Marine Mattress (0.332) occupied the mid-range, while Coastalock (0.244), Bio Active Standard (0.200), and Sea Wall Panels (0.091) ranked lowest. Sea Wall Panels' low ratio is particularly notable given their large physical scale their expansive but largely planar surfaces yield a relatively narrow void margin despite overall volume. These ratios function as geometric proxies for niche availability, reflecting the principle that void spaces within and between structural elements facilitate species coexistence and recruitment (Liversage & Chapman, 2018). They do not, however, constitute direct predictions of biodiversity outcomes, and should be interpreted accordingly.

4.3 RANKING ALIGNMENT AND MISMATCHES

The two assessment methodologies showed substantial concordance, with 71% agreement in ordinal rankings (Table 1). Classic Tidal Pools and Bio Active Pocket consistently occupied the top tier; Eco Armor Block held a stable mid-rank position; and Sea Wall Panels and Bio Active Standard anchored the bottom across both methods. This convergence supports the ecological validity of the visual scoring framework modules perceived as structurally complex also demonstrate greater geometric void efficiency.

The mismatches, however, are analytically informative. Bio Active Pocket ranks first quantitatively but second visually: its superior void ratio is offset perceptually by its low Organic Form Factor score (1.03/5), suggesting that assessors underweighted its geometric efficiency relative to its visual naturalness. Conversely, Marine Mattress and Coastalock exchange positions between methods Marine Mattress's relatively strong edge scores (2.95/5) boost its visual ranking despite a moderate habitat ratio, indicating that edge articulation carries disproportionate perceptual weight. These divergences are not methodological inconsistencies; rather, they reveal the complementary nature of perceptual and geometric assessments and justify the integrated approach taken in this study.

Table 01: Visual total scores and habitat potential ratios for seven ECOncrete modules. Visual scores are mean values from the expert panel on a 100-point weighted scale. Habitat potential ratio = void volume / solid module volume.
(Source: Author)

Module	Visual total score (/100)	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

4.4 EXPLORATORY FEATURE-IMPORTANCE ANALYSIS

To incorporate the resilient intelligence layer described in Sections 1 and 3.9, an exploratory Random Forest feature-importance analysis was applied to the aggregated scoring dataset. As noted in the methodology, this analysis is explicitly exploratory given the small module sample (n = 7), and results should be interpreted as indicative sensitivity signals rather than robust predictive outputs. Surface Topology (importance = 0.22) and Edge Complexity (0.20) emerged as the two most influential features in relation to habitat potential ratios, followed by Internal Void Architecture (0.15) (Figure 4). These findings are consistent with the broader ecological literature, in which surface rugosity and edge irregularity are established primary drivers of marine species richness and abundance (House et al., 2016; Lee et al., 2005). For future module design, this suggests that investment in surface texture refinement and edge articulation would yield the greatest gains in ecological habitat potential, ahead of improvements in shelter provision or organic form though the latter two remain important areas of current underperformance.

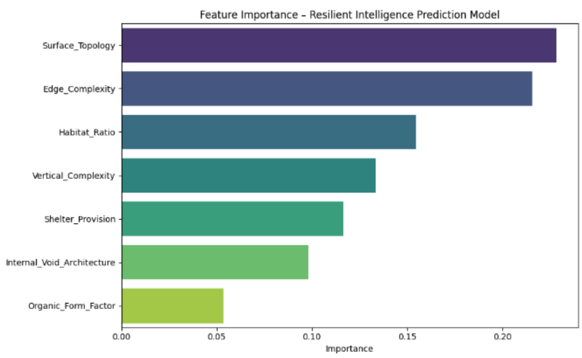

Figure 6: Exploratory Random Forest feature-importance scores for six ecological design attributes in relation to habitat potential ratios (n = 7 modules). Results are indicative only.
(Source: Author)

4.5 DISCUSSION: HABITAT COMPLEXITY AND BIOMIMETIC DESIGN IMPLICATIONS

The results reveal a consistent pattern across both assessment methods: modules that achieve high surface rugosity, edge articulation, and internal void provision demonstrate the strongest ecological habitat potential. This aligns with foundational ecological theory linking structural heterogeneity to niche diversity and species richness (MacArthur & MacArthur, 1961; House et al., 2016). The high performance of Classic Tidal Pools across both methods reflects the ecological dividend of closely mimicking natural intertidal morphology, a finding consistent with evidence that biomorphic design features improve larval settlement and early community assembly (Perkol-Finkel et al., 2012).

The consistently low scores for Shelter Provision and Organic Form Factor across all seven modules point to a systematic design gap. Current modules appear to prioritise surface complexity and void provision attributes that are more readily achievable through standard manufacturing processes at the expense of deeper sheltering geometry and naturalistic morphology. Sea Wall Panels exemplify this limitation: their large planar surfaces provide substantial structural coverage but minimal void architecture, yielding the lowest habitat potential ratio (0.091) in the dataset and suggesting limited capacity to support diverse species assemblages (Bulleri & Chapman, 2010).
Bio Active Pocket's performance warrants particular attention. Its quantitative primacy (ratio 1.540) despite a moderate visual score (71.7) suggests that compact, void-efficient geometries may be undervalued in perceptual assessments relative to their actual ecological potential. When deployed in aggregated reef patch configurations, such modules could achieve collective habitat complexity considerably exceeding what individual visual scores imply an insight with practical relevance for reef patch design and module selection decisions.

It is important to emphasise that all ecological performance interpretations in this study are based on geometric and perceptual proxies. The habitat potential ratios and visual scores used here represent indicators of ecological suitability, not demonstrated biodiversity outcomes. Field-based biological validation through settlement monitoring, species surveys, and long-term ecological assessment remains an essential next step before any module can be definitively characterised as ecologically superior. The present framework is best understood as a design screening tool that enables comparative evaluation prior to deployment, rather than a substitute for empirical ecological assessment.
From a design and policy perspective, the findings suggest that incorporating geometric complexity metrics, particularly void-to-solid ratios and surface rugosity thresholds, into green product certification frameworks could provide a more objective basis for evaluating ecological credentials of coastal infrastructure products. However, such applications would require the framework to be validated against field biological data before adoption in regulatory contexts.

5. Limitations and future research directions

This study represents a pilot-scale exploratory framework, and several limitations should be acknowledged explicitly when interpreting its findings.

First, the absence of field-based biological validation is the most significant constraint. All ecological performance assessments in this study rely on geometric proxies' void-to-solid ratios and visually scored surface attributes rather than on observed species data. Habitat potential ratios indicate structural suitability for colonisation but do not constitute evidence of actual biodiversity outcomes. The relationship between geometric complexity and species richness, while well-supported in the broader literature (House et al., 2016; Liversage & Chapman, 2018), has not been empirically verified for these specific modules in real deployment conditions. Field-based validation through settlement monitoring, macrofaunal surveys, and long-term ecological assessment across deployed ECOncrete modules is therefore an essential and urgent next step.

Second, the visual scoring process is inherently subjective. Although the calibration and contextual priming exercise using SimScale visualisations was designed to promote consistency, the priming process itself may have introduced perceptual anchoring effects, whereby assessors' interpretations of features were influenced by the flow visualisations viewed prior to scoring. Assessors were not blinded to module identity or manufacturer, which may have introduced familiarity bias for those with prior knowledge of ECOncrete products. Future studies should implement formal blinding procedures and structured inter-rater reliability testing using intraclass correlation analysis or similar with a larger, formally stratified panel to establish the robustness of the scoring framework.

Third, the pilot expert panel used in this study represents a convenience sample appropriate to an exploratory investigation. The panel size and composition were not formally randomised or stratified, limiting the generalisability of scoring patterns across broader professional populations. A larger-scale validation study with a pre-registered recruitment protocol and disciplinary stratification would strengthen confidence in the perceptual rankings reported here.

Fourth, the dimensional adjustments applied to two modules, Classic Tidal Pools and Sea Wall Panels to resolve negative void values introduce uncertainty into their habitat potential ratios. These adjustments were minor and conservative, but the resulting ratios for these two modules should be treated as approximations. Future work should obtain precise manufacturer-verified volumetric data to eliminate this source of imprecision.

Fifth, the exploratory Random Forest feature-importance analysis was conducted on a dataset of seven modules far below the sample size conventionally required for robust machine learning inference. The results should be interpreted strictly as indicative sensitivity signals within this dataset, not as generalisable predictive relationships. Future applications of this resilient intelligence framework would benefit from a larger comparative module dataset,

potentially incorporating modules from multiple ecological engineering manufacturers, to improve the statistical reliability of feature-importance outputs.
Future research directions arising from these limitations include:

(1) Field trials validating habitat potential ratios against observed macrofaunal diversity and settlement density across deployed ECOncrete modules in contrasting biogeographic contexts;
(2) Fractal dimension analysis of module surfaces to provide an objective geometric complement to visual edge complexity scores;
(3) Formal inter-rater reliability testing of the visual scoring framework with a larger stratified panel;
(4) Extension of the comparative framework to include modules from other ecological engineering manufacturers; and
(5) Longitudinal ecological monitoring of reef patch deployments to assess community succession trajectories relative to module type.

6. Conclusion

This study developed and applied a semi-quantitative framework for evaluating the ecological habitat complexity of seven ECOncrete coastal protection modules, integrating structured visual scoring with quantitative volumetric analysis and exploratory feature-importance modelling. The framework operationalises a resilient intelligence perspective defined here as the deliberate integration of expert perceptual judgement with computational sensitivity analysis to move beyond descriptive module ranking toward actionable guidance for biomimetic design optimisation.

The findings reveal a consistent performance hierarchy across both assessment methods. Classic Tidal Pools demonstrated the strongest overall ecological potential (visual score 89.0; habitat ratio 0.760), reflecting close morphological mimicry of natural intertidal forms and high scores across surface topology, edge complexity, and internal void architecture. Bio Active Pocket led quantitatively (habitat ratio 1.540) despite a moderate visual score (71.7), highlighting the underappreciated ecological potential of compact, void-efficient geometries when deployed at reef patch scale. Eco Armor Block and Marine Mattress demonstrated moderate potential, while Sea Wall Panels and Bio Active Standard consistently underperformed, constrained by planar surfaces and limited void provision.

The 71% concordance between visual and quantitative rankings supports the validity of structured expert scoring as a reliable proxy for geometric habitat assessment in the absence of field data. The ranking mismatches particularly Bio Active Pocket's quantitative primacy and Marine Mattress's visual over-performance are not inconsistencies but informative divergences that illuminate the relationship between perceptual complexity and measurable void efficiency.

The exploratory feature-importance analysis identified Surface Topology and Edge Complexity as the attributes most strongly associated with habitat potential ratios, suggesting these should be prioritised in future module design iterations. The consistently low scores for Shelter Provision and Organic Form Factor across all modules point to a systematic design gap; current units favour geometric simplicity for manufacturability over the naturalistic morphology that would maximise ecological integration with natural reef communities.

All ecological performance interpretations in this study are based on design proxies and should be understood as indicators of habitat suitability, not as demonstrated biodiversity outcomes. Field-based biological validation is the critical next step. Subject to that validation, the framework presented here offers a practical, transferable screening tool for landscape architects, coastal engineers, and ecological practitioners engaged in the evaluation, selection, and design of biomimetic coastal infrastructure. With further development, habitat complexity metrics of the type explored in this study could inform evidence-based criteria for green product certification in coastal construction, contributing to more ecologically grounded governance of nature-based coastal solutions.

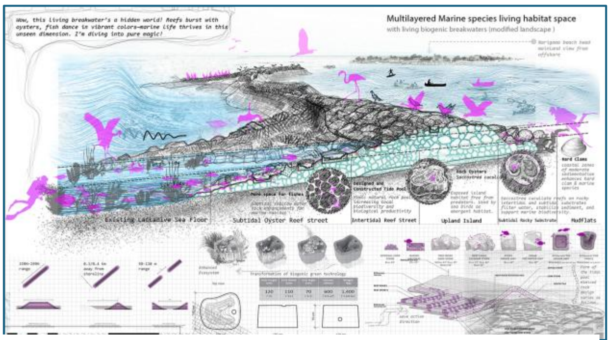

Figure 7: Conceptual spatial arrangement of living breakwaters using Classic Tidal Pools as primary building units, illustrating an adaptive reef patch configuration. (Source: Author — conceptual design)

7. Citations, References and Acknowledgements

7.1. REFERENCES

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