ISSN 2386-5414
e-ISSN: 2340-8391

Research article

Industrial Design for bio-inspired solutions in coastal protection

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Received: April 25, 2025 | Accepted: June 28, 2025 | Published: June 29, 2025

DOI:10.24310/p56-idj.5.1.2025.21715

Abstract

Coastal erosion, extreme climatic events, and biodiversity loss are major consequences of climate change, posing significant threats to both the environment and society. Addressing these challenges has led to a growing focus within industrial design on innovative, interdisciplinary approaches inspired based bioinspired design. Natural ecosystems have evolved over millions of years to create highly efficient structures that dissipate wave energy, stabilize shorelines, and support biodiversity, offering valuable models for sustainable coastal protection. These biological principles serve as a reference model for the design of high-performance and sustainable coastal defense solutions.

This study reviews the state of the art in coastal protection systems and introduces the conceptual development and preliminary experimental validation of simplified bioinspired models designed to enhance shoreline resilience. The hydraulic efficiency of these models was assessed through experimental testing, exploring their potential as innovative mitigation strategies against irregular and extreme wave conditions.

This research contributes to the development of next-generation submerged barriers, inspired by the morphology and functionality of natural systems, constructed from sustainable materials, and optimized for both hydraulic efficiency and ecological support. Following a top-down approach, key functional traits of biological structures were analyzed, abstracted, and translated into three distinct bioinspired design solutions for coastal protection.

The results provide a foundation for advancing sustainable coastal protection strategies, demonstrating the added value of bioinspired solutions in enhancing both shoreline resilience and ecological integration.

Keywords: Enviromental Design; Biometics; Ecodesign; Design for sutanaibility, Coastal Protection

Introduction

Climate change is accelerating, bringing well-documented consequences such as sea level rise, coastal flooding, erosion, and more frequent extreme weather events (IPCC, 2023; Di Luccio et al., 2018). Coastal zones -key areas of rich ecosystems and nearly 40% of the global population - are increasingly vulnerable due to rising seas, intensified storm activity, and unregulated urban expansion (IPCC, 2021–2023). At the same time, unsustainable exploitation of resources and ecosystem degradation threaten both environmental balance and the livelihoods of coastal communities.

In response, new economic models such as the Blue Economy (Pauli, 2009) emphasize the sustainable and regenerative use of marine resources. This paradigm supports economic, social, and ecological value creation through nature-based and technology-driven solutions promoting low-impact activities like renewable marine energy, sustainable fisheries, and responsible tourism. Within this framework, design becomes strategic: a tool to develop resilient coastal solutions that reconcile environmental protection with long-term development goals.

Coastal barriers are central to this challenge, offering critical regulation and protection services (Bridges et al., 2013; Unguendoli et al., 2023). Historically, these have included emerged or detached breakwaters, massive structures built parallel to the shoreline, dating back millennia (Haggi, 2010). While effective at dissipating wave energy (Franco, 1996; Sharifahmadian, 2015), such “grey” infrastructure has caused unintended damage, including current disruption, seabed degradation, and landscape alteration (Hawkins et al., 2015; Saengsupavanich, 2022; Perricone et al., 2023).

In the 1980s, engineers introduced low-crested submerged breakwaters (SBs) (Browder et al., 1996), initially seen as more environmentally benign. However, only in the last decade, thanks in part to EU projects like THESEUS and DELOS (THESEUS, 2024; DELOS, 2024), have their ecological impacts been thoroughly examined. While SBs minimize visual intrusion, they can disrupt sediment transport and, under certain conditions, accelerate shoreline erosion (Postacchini et al., 2016; Duarte Nemes et al., 2019; Ranasinghe et al., 2006).

More permeable SBs have been proposed to mitigate these issues (Hur et al., 20129), and the bio-inspired approach explored in this study follows this direction. Yet, the link between permeability and sediment dynamics remains poorly understood. As grey infrastructure shows its limits, a growing shift toward green, adaptive, and ecologically integrated solutions is gaining momentum (Singhvi et al., 2022). This article revisits a bio-inspired design model discussed and explored in detail in the article “Biopinspired Coastal Barriers” by Perricone et al. (Perricone et al., 2024).

Nature-Based Solutions, Bio-Inspired Approach, and Design Invention

Within the landscape of contemporary design, the bio-inspired approach emerges not as a superficial mimicry of nature’s aesthetic, but as a deep cognitive and methodological strategy grounded in the systemic observation of the living world. Nature is understood here as a dynamic system one that organizes, adapts, and evolves through complex processes over vast evolutionary timescales. From this perspective, designers extract models of resilience, efficiency, and optimization, translating them into operative tools capable of addressing the systemic complexity of today’s environmental, technological, and social challenges.

This interdisciplinary lens had already been anticipated in the early 1970s by Victor Papanek, who attributed to design a proactive and ethical role in shaping solutions to ecological and social issues. For Papanek, nature was not only an aesthetic source but also a methodological guide for the development of sustainable and adaptive models (Papanek, 1971; Skjerven, 2019). This position contributed to a broader epistemological shift: design began to be redefined not merely as a formal discipline but as a critical and generative practice, oriented toward emergent needs and capable of reshaping the relationships between form, function, and technological innovation (Buono, 2018).

The present contribution emerges from this lineage and proposes a bio-inspired design approach aimed at mitigating the impacts of wave motion on vulnerable coastal zones. The research developed through a collaborative and interdisciplinary process, incorporating diverse domains of knowledge from morphology and biomimetics to computational modeling, materials science, and hydrodynamic simulation. In a hyper-technological and rapidly evolving context, the designer-as-inventor operates within networks of collaboration and knowledge transfer, where innovation arises through cross-contamination and the reconfiguration of disciplinary boundaries (Buono, 2018).

Such an integrative approach activates what can be described as distributed design intelligence, oriented toward the development of sustainable and adaptive solutions. In this context, bio-inspired design does not merely imitate natural forms, but leverages biological strategies as catalysts for systemic invention producing scalable, efficient, and context-sensitive outcomes.

Two complementary trajectories shaped the methodological framework of this research. The first concerns "designing according to nature", where functional principles observed in biological systems are abstracted and transferred into industrial design processes. The second involves "designing for invention", whereby the design process becomes a space for radical exploration, generating new functions, new meanings, and previously unarticulated relationships among systems, materials, and environments.

The concept of Design for Patent exemplifies this dual commitment. It represents not only a path toward intellectual property creation but also a broader interpretative and epistemological platform, through which technical, cultural, and scientific dimensions converge to produce original systems and components (Capece et al., 2019; 2020). This approach enables the definition of a shared ontological and linguistic domain (what we might call a patent vocabulary) that structures innovation within a transdisciplinary framework.

Rather than producing mere visual or formal novelty, the objective becomes the generation of meaningful design: forms that respond to latent needs, enhance everyday life, and operate within regenerative ecological logics. Historic figures like Borromini and D'Ascanio remind us that invention and vision have long converged in the most impactful forms of design, where the artifact is both technically sound and culturally transformative (Buono, 2018).

Today, technologies such as 3D printing, topological optimization, and FEM simulations allow biomimetic strategies to be translated into adaptive geometries that can be digitally and then experimentally tested and validated. Through this lens, the interaction between biological intelligence, digital modeling, and material science creates a productive design space where conceptual ideas are transformed into resilient, high-performance systems.

The convergence between bio-inspired design and invention thus outlines an expanded framework for contemporary practice: one that transcends binary oppositions between nature and artifice, form and function, engineering and creativity. Here, design is redefined as a systemic act, i.e., a practice that is simultaneously ecological, aesthetic, and political. Through this synthesis, the artificial-natural divide is overcome, and the design process itself becomes a tool for sustainable innovation, weaving together ecological, social, and technological threads within a dynamic and meaningful whole (Flusser, 2003).

This expanded role is particularly relevant to the development of new coastal infrastructures, where the imperative is not only to reduce erosion or dissipate wave energy, but to create morphologies that support biodiversity and minimize environmental disruption. Nature-Based Solutions (NbSs) offer a compelling pathway in this regard, using habitats such as seagrass meadows, coral reefs, and mangroves to stabilize coasts and provide essential ecosystem services (Bridges et al., 2013; Narayan et al., 2016; Perricone et al., 2024).

However, these strategies are not without limitations: they often require long timeframes, extensive spatial requirements, and are sensitive to anthropogenic and seasonal variables (Schoonees et al., 2019; Seddon et al., 2020). For this reason, hybrid systems combining natural habitat creation with artificial scaffolding, are increasingly adopted to ensure immediate effectiveness and structural reliability in high-turbulence contexts (Stachew et al., 2021; Perricone et al., 2024).

The development of 3D-printed artificial reefs, some explicitly bio-inspired, represents a recent trend in this field. Notable examples include the Modular Artificial Reef Structure (MARS) by Reef Design Lab (Reef Design Lab, 2025) and 3DPARE modules for coral reef restoration (3DPARE, 2025). Of particular interest is the work by Stachew, Houette, and Gruber (2021), who proposed a mangrove-inspired barrier system demonstrating the feasibility of translating natural growth strategies into multifunctional infrastructural designs.

Objectives of the Study

In an international context marked by the urgency of integrated, sustainable transitions, reflected in initiatives such as the UN 2030 Agenda, the European Green Deal, and the New European Bauhaus, this research seeks to offer a design-led contribution to the discourse on coastal resilience.

The aim of the study is to explore the potential of bio-inspired geometries for the development of next-generation coastal barriers. Through a top-down design approach, the project identifies critical challenges and opportunities in wave energy dissipation, abstracts key functional traits from biological models, and translates them into simplified yet scalable prototypes. These are then tested under controlled conditions to evaluate their capacity for wave transmission, reflection, and dissipation.

This work is part of a broader design vision: the speculative construction of a "submerged forest", composed of artificial yet bio-integrated barriers that protect and regenerate the marine ecosystem. In this vision, technical performance is not detached from ecological and cultural significance but fully embedded within it.

Three prototypes were developed and experimentally tested to assess their hydrodynamic efficiency. This methodological path involved critical evaluation of biological strategies, patent precedents, and structural feasibility within an interdisciplinary research environment bringing together designers, engineers, and marine biologists within the Department of Engineering at the University of Campania "Luigi Vanvitelli."

The result is not merely a sequence of experiments, but the formulation of a design ontology grounded in invention. The project engages with new "cultural, technological, social, and mental landscapes," as Capece et al. (2019) suggest, recasting the act of invention not as a terminal goal, but as an interpretive and generative tool. The Design for Patent framework becomes both a lens for understanding complexity and a method for structuring innovation.

Ultimately, the study proposes a set of preliminary solutions that aim to integrate wave energy dissipation, ecological permeability, and material adaptability into a unified system. These prototypes demonstrate the potential of a design practice that is not only responsive, but visionary, which are capable of navigating the intersections between environmental urgency and creative possibility.

Methodology, design development

This research explores a bio-inspired approach as a critical and creative framework for rethinking coastal infrastructures. Nature, understood not as a mere aesthetic reference but as a systemic and intelligent source of knowledge, becomes both model and mentor in the development of multifunctional and ecologically integrated solutions (Chayaamor-Heil et al., 2023).

This paradigm is particularly relevant in the design of coastal barriers, where the need for protection intersects with the opportunity to generate habitats and foster biodiversity (Perricone et al., 2023; Stachew et al., 2021).

From a general methodological standpoint, translating natural strategies into design applications involves five core phases (Figure 1):

- 1. Problem Definition: Understanding the design needs and constraints; identifying the specific challenges to be addressed.
- 2. Identification of Biological Strategies: Studying natural models (organisms and ecosystems) to recognize relevant strategies in similar contexts.
- 3. Abstraction of Functional Mechanisms: Extracting key characteristics or mechanisms and converting them into applicable design principles.
- 4. Transfer: Contextualize and adapt the abstracted models to the designing of new artefacts
- 5. Development and Evaluation: Designing and assessing proposed solutions in terms of performance and feasibility, including modeling and testing activities (Perricone et al., 2024).

The project unfolds through a design-driven methodology that merges environmental sciences, sustainable engineering, and industrial design. At its core lies the reinterpretation of natural logics biological structures, adaptive mechanisms, and ecological strategies into engineered artifacts. This translation is not imitative but interpretative, requiring abstraction, critical framing, and contextualization. The process begins by identifying the ecological and infrastructural challenges posed by increasing coastal erosion particularly in contexts like Italy, where over 1,000 km of coastline are currently exposed to erosive dynamics (ISPRA, 2022). These areas are often environmentally and socioeconomically fragile, and conventional engineering responses have proven insufficient or unsustainable, both in terms of material impact and spatial consequences.

Traditional coastal infrastructures, such as seawalls, groins, and rubble-mound breakwaters, are typically rigid, mono-functional, and materially intensive. While effective in wave attenuation, they often introduce new environmental disturbances and lack the adaptive capacity required in the face of climate change. Their homogeneity reduces habitat complexity and may inhibit marine biodiversity, even encouraging the proliferation of invasive species (Bulleri et al., 2010; McLachlan et al., 2018). Moreover, their construction and maintenance involve high resource consumption and significant CO_2 emissions, raising questions of long-term ecological and energetic viability.

In contrast, the bio-inspired perspective proposes an alternative mode of thinking: one in which design is informed by nature's capacity for resilience, interdependence, and multifunctionality. From a methodological standpoint, the project follows a top-down trajectory, beginning with a critical analysis of context and proceeding through

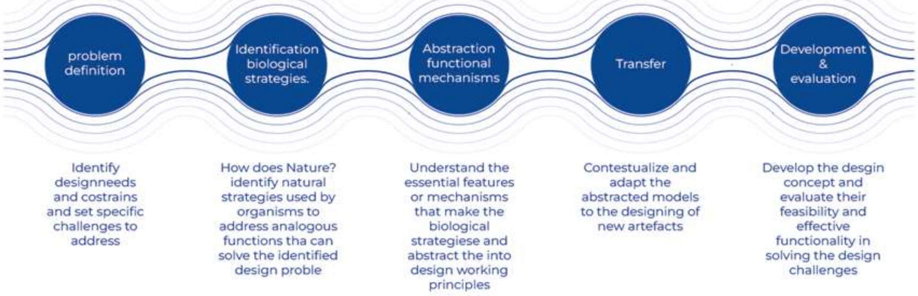

Figure 1. This diagram shows the phases followed in the bio-inspired design process.

the exploration of natural analogues. The abstraction of biological principles such as surface modulation, porosity, modular growth, and dynamic feedback is then rearticulated through design. This process leads to the conceptualization of a new generation of coastal devices that are not only protective, but also regenerative, porous to flows (hydrodynamic and ecological), and compatible with local ecosystems.

A review of existing technologies, including both traditional breakwaters and more recent hybrid solutions, highlights the limitations of current systems. Several patented designs such as WO2013081352A1 (2012) and US4818141 (1989) illustrate standardized approaches based on modular concrete units engineered for wave dissipation. Despite their structural efficiency, these systems often rely on precise calibrations and are vulnerable to environmental changes. Their rigid geometries and impermeable bodies contrast sharply with the complexity of marine systems. Likewise, innovations that integrate wave energy harvesting such as US8004105B2 (2011) or EP3078844B1 suggest a shift toward multifunctionality, but remain constrained by technological complexity, limited permeability, and challenges in maintenance and adaptability.

In summary, both categories, traditional coastal defenses and hybrid energy-generating systems, highlight the urgent need for a new generation of multifunctional, adaptable, and ecologically integrated solutions.

The design hypothesis developed here seeks to overcome these criticalities through a systemic and responsive design logic. Rather than imposing static forms onto dynamic environments, the aim is to create infrastructural systems that interact with marine processes, encouraging sediment deposition, biotic colonization, and energy dissipation through form and materiality. The result is not a finished object but an open system: modular, repairable, and ecologically embedded. It is precisely this convergence between design culture, ecological intelligence, and material ethics that defines the project's contribution to contemporary discourse on resilient infrastructures.

Ultimately, the bio-inspired breakwater conceived through this methodology does more than resist waves: it proposes a new relational model between human infrastructure and natural systems. One that is not extractive, but co-productive.

Bio-Inspired strategy and design development

Rethinking coastal protection in the face of climate intensification, erosion, and habitat loss demands a radical shift from inert engineering to responsive, living systems. Natural environments have long embodied resilient strategies of adaptation, protection, and regeneration. Marine ecosystems such as coral reefs, oyster beds, mangrove forests, salt marshes, and seagrass meadows stand out as sophisticated infrastructures shaped by evolution over geological time scales (Perricone et al., 2024). Far from being passive landscapes, these systems actively modulate hydrodynamic forces, stabilize sediments, and enhance biodiversity while also providing essential ecosystem services like carbon sequestration, water filtration, and local climate regulation (Narayan et al., 2016; Barbier, 2012).

Within this ecological repertoire, seagrass meadows emerge as especially relevant models for bio-inspired design. These submerged plant systems such as Posidonia oceanica, endemic to the Mediterranean have adapted morphologically and physiologically to the marine photic zone over 70 million years. Anchored by dense networks of roots and rhizomes, they form expansive underwater carpets capable of trapping sediments, slowing currents, and dissipating wave energy along the water column. More than biological organisms, these systems act as ecological engineers: enhancing seabed stability, offering habitat to marine life, and acting as dynamic buffers between sea and shore (Perricone et al., 2023; Ondiviela et al., 2014).

What makes seagrasses particularly compelling as design analogues is their dual role structural and ecological. Their distributed, flexible geometries interact fluidly with water, altering flow without resisting it, transforming motion into equilibrium. In contrast to rigid barriers, these systems absorb and adapt. Emulating them suggests more than biomimicry: it opens the door to a new design ethic one that envisions infrastructure as porous, adaptive, and coexistent with the ecosystems it occupies.

From this theoretical and ecological framework, the research moves toward design translation. Hydrodynamic studies of seagrass meadows have identified several critical principles: submerged vegetation dissipates wave energy through flow redirection and turbulence induced by friction. Factors such as plant density, biomass, leaf stiffness, and the submergence ratio (plant height relative to water depth) are key in determining the extent of attenuation (Ondiviela et al., 2014; Cavallaro et al., 2018). Meadows with greater vertical occupation of the water column demonstrate more effective reduction of wave forces (Fonseca et al., 1992; Augustin et al., 2009; John et al., 2016). Notably, John et al. (2016) identified the most influential parameters in wave transmission as relative plant height, meadow density, and the width of vegetated areas wider meadows reducing wave run-up by up to 41%. These insights were abstracted and synthesized into a set of bio-inspired design hypotheses (Figure 2).

The objective was not to replicate natural forms, but to distill their functional logic into engineered components for coastal protection systems that move beyond mere resistance. The proposed solutions aim to merge defense, adaptability, and environmental performance through modular structures that integrate seamlessly with dynamic marine environments.

Among the features of the proposed system are:

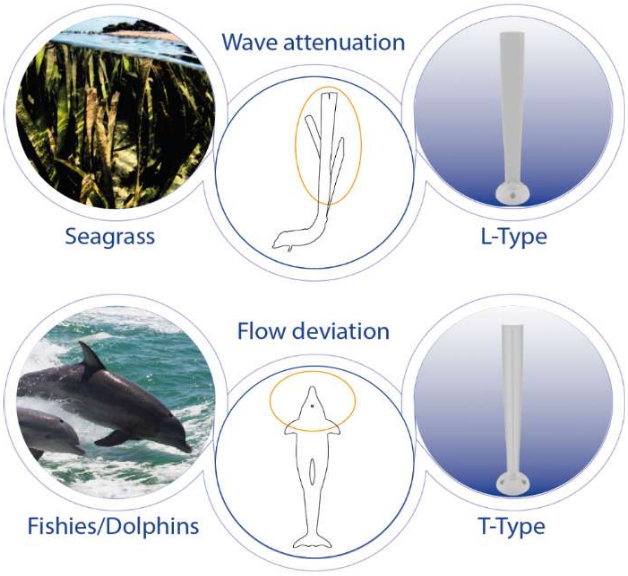

Figure 2. This figure shows the marine organisms that inspired the shape and function of the breakwater modules.

- The conversion of omnidirectional wave motion into kinetic or electrical energy, allowing for renewable energy generation in varying sea conditions.
- Adaptability and reversibility, with installation possible on different seabed types.
- Low-impact assembly, ease of disassembly and relocation.
- Strong ecological integration, encouraging colonization and sediment stability.
- The ability to attenuate wave energy, particularly from storm surges and extreme marine weather events.

The research situates itself within the field of maritime infrastructure design, seeking to reconceive elements like seawalls and breakwaters not as impermeable monoliths, but as responsive ecotechnical systems. The project led to the development of four primary prototype morphologies, informed by the biomechanical principles of seagrass meadows and hydrodynamic efficiency:

- L-Type: Inspired by the flat, elongate shape of Posidonia leaves, designed for low resistance and high sediment interaction.

- T-Type: Characterized by a triangular cross-section, optimized to redirect wave flow and enhance impact resistance.

- HT-Type: A hybrid variant of the T-Type, integrating a circular upper module to increase visibility and enable the mounting of environmental sensors or navigational instruments.

- C-Type: A simplified cylindrical geometry developed for controlled testing of drag and flow behavior.

The T-Type model, in particular, draws inspiration from the streamlined shapes of aquatic organisms such as dolphins and pelagic fish, whose elongated bilateral morphologies reduce drag and allow rapid, forceful reentry into water (Perrin et al., 2009; Jung, 2021). These principles were adapted into geometric forms capable of dissipating wave energy while resisting structural fatigue.

Experimental Configuration and Data Analysis

All prototypes were developed using Rhinoceros 3D (v7) and fabricated through Fused Deposition Modeling (FDM) with an Anycubic Chiron 3D printer. The selected material PETG (Polyethylene Terephthalate Glycol) was chosen for its mechanical strength, chemical resistance, thermal stability, and recyclability, aligning with the project's circularity goals. The models were printed at a 1:25 scale, respecting Froude similarity for hydrodynamic testing, with a layer height of 0.20 mm, 20% infill density, and a print speed of 50 mm/s.

This first phase of experimental development marks a critical step in the exploration of bio-integrated infrastructures systems that do not dominate the marine environment but dialogue with it, adapting to its dynamics, and, in doing so, transforming the role of coastal defense into one of ecological collaboration.

The geometric and dimensional specifications of the prototypes are detailed in Figure 3 and Table 1

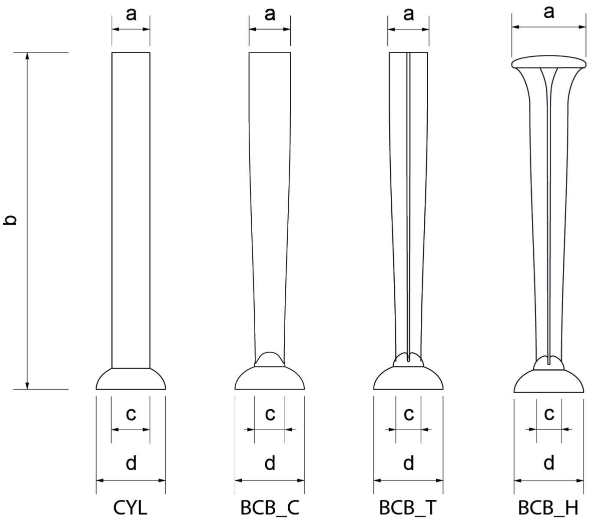

Figure 2. Model prototypes: technical drawing indicating (a) upper width, (b) height, (c) lower width, and (d) base diameter. Corresponding dimensions are provided in Table 1.

Table 1. Main geometrical parameters of the tested models. All measurements are given in millimetres (mm).

	a (mm)	b (mm)	c (mm)	d (mm)
CYL	27	250	27	50
BCB_C	30	250	20	50
BCB_T	27	250	18	50
BCB_H	53	250	18	50

The models were subsequently tested in a laboratory setting to evaluate their hydrodynamic performance and their effectiveness in dissipating wave energy. The results of these experiments are discussed in the following sections.

In a time marked by accelerating erosion and intensifying climate phenomena, the defense of coastal landscapes can no longer rely on inert, monolithic infrastructures. The experimental work presented here explores an alternative line of inquiry: the testing of bio-inspired, modular geometries developed through digital fabrication and deployed under controlled wave conditions. Conducted at the Maritime Engineering Laboratory of the University of Campania "Luigi Vanvitelli," the research examines the hydrodynamic behavior of prototypes designed not to resist nature, but to engage

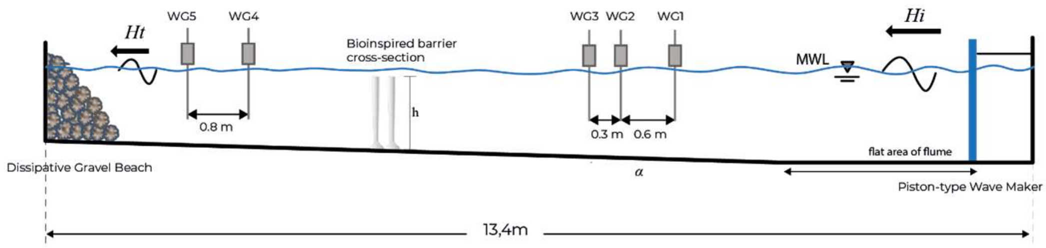

Figure 4. Schematic representation of the wave flume and the experimental setup.

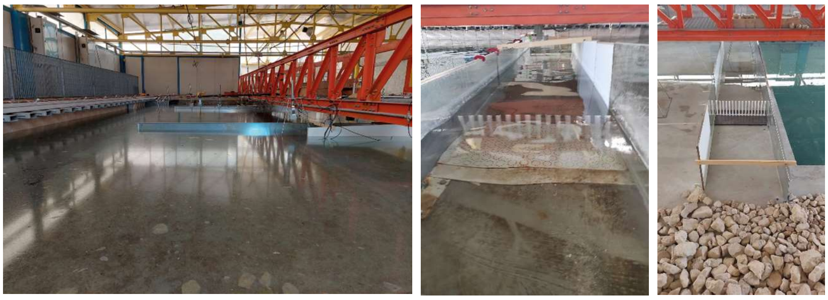

Figure 5. Photographic view of the laboratory setup and model arrangement.

with its fluid logics. The experimental apparatus was set up within a 13.4 m long, 0.8 m wide, and 0.6 m deep wave flume, featuring a non-erodible bottom and a 3 m flat initial section followed by a sloped seabed inclined at a 1:22 gradient, simulating nearshore bathymetry (Figures 4 and 5).

A piston-type paddle system, controlled via AwaSys software (v5, Aalborg University, 2010), generated regular and irregular wave conditions with active reflection absorption. A gravel beach placed at the downstream end dissipated residual wave energy and minimized re-reflections. Open lateral boundaries ensured hydrodynamic circulation behind the models, avoiding artificial pressure buildup.

Wave data was collected through a system of five resistive gauges positioned according to Klopman and van der Meer's method (Klopman et al., 1999), enabling the calculation of incident and reflected components using the Mansard and Funke separation technique (Mansard & Funke, 1980). Sampling was conducted at 30 Hz, and the transmission coefficient (Kt) served as the principal metric for evaluating wave attenuation across all configurations.

Six experimental configurations were tested, each composed of sixteen printed units mounted on a CNC-milled, perforated steel plate (800 mm × 439 mm × 20 mm). The T-Type and HT-Type morphologies, based on a triangular profile, were also tested in inverted orientations (rT-Type and rHT-Type), with their bases rotated 180° toward the incoming wave (Figure 6).

These modifications were introduced to study the effect of geometric directionality on performance.

Four distinct wave regimes were generated:

- Weak regular waves (Hi < 0.06 m), simulating low-energy sea states.
- Moderate regular waves (0.07 m < Hi < 0.14 m), corresponding to average energy conditions.
- Extreme regular waves (0.15 m < Hi < 0.20 m), just below breaking thresholds.
- Storm irregular waves (Hi = 0.14 m), with peak periods of 0.8, 1.2, and 1.6 seconds, based on a JONSWAP spectrum (γ = 3.3).

This classification was conceived to replicate the variability of real-world marine dynamics, from calm to turbulent. The wave steepness (s), defined as the ratio of height to wavelength, was adopted as a key interpretive parameter in assessing energy transformation and dissipation processes.

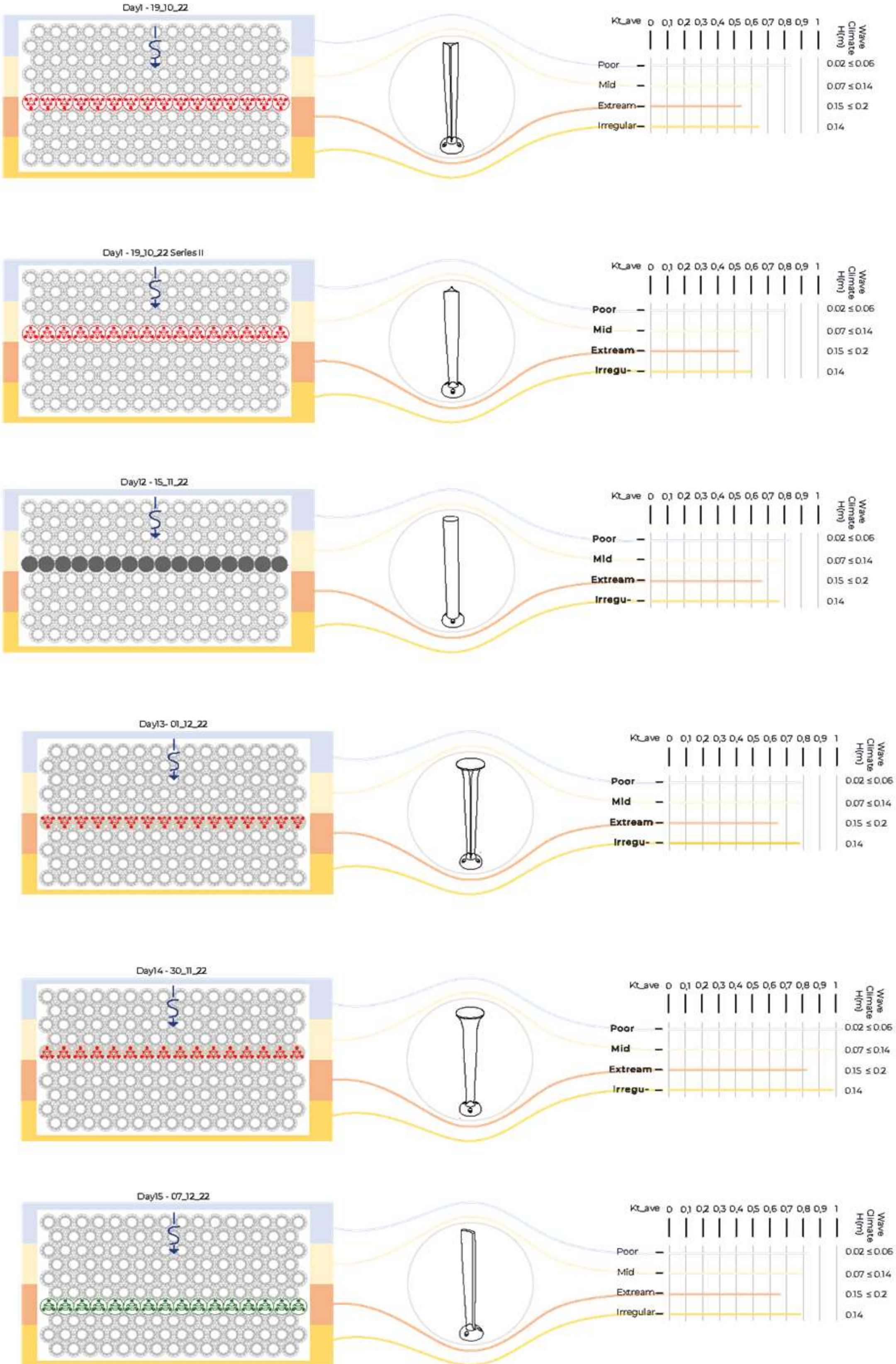

Figure 6. Schematic diagram of the model distribution set-up in the different configurations and representation of the data collected.

The results (Figure 6) revealed clear differences in performance across morphologies. The C-Type, cylindrical and symmetrical, behaved as expected: consistent and relatively unresponsive to varying wave energies, serving as a neutral hydrodynamic reference. The T-Type consistently demonstrated the lowest Kt values, effectively dissipating wave energy across all conditions. Conversely, the inverted rT-Type showed a degradation in performance, highlighting how orientation affects the interaction between form and flow.

The HT-Type, featuring a cylindrical upper head, showed decreased efficiency compared to its base form an effect amplified in the rotated configuration (rHT-Type), where transmission increased by 18%. This suggests that the added mass or altered turbulence patterns introduced by the upper element may disrupt the flow redirection mechanisms fundamental to its intended function.

When compared with traditional rock breakwaters which average Kt values between 0.41 and 0.42 under similar wave regimes (Hassanpour et al., 2023) the bio-inspired prototypes yielded promising results. The rT-Type, for instance, achieved average transmission coefficients of 0.65 under weak, moderate, and extreme conditions, and 0.61 during storm simulations. This is particularly significant given that only a single row of units was deployed, whereas conventional systems require substantial material volumes and seabed coverage to perform similarly.

Beyond numerical comparisons, the behavior of the models points to an adaptive logic. In low-energy conditions, higher transmission may be ecologically beneficial: it supports water exchange, sediment transport, and oxygen circulation, helping to avoid stagnation and allowing natural processes to persist. Under storm conditions, the sharp drop in Kt values ensures effective wave attenuation, reducing the risk of coastal flooding and erosion.

The poor performance of the HT-Type suggests a need for further morphological optimization. One hypothesis attribute this to the interference generated by the upper cap, which may alter pressure fields and inhibit desired turbulence patterns at the model's base. Future iterations will explore alternative head forms and sectional voids to improve hydrodynamic responsiveness.

A critical dimension of the study is the volumetric and environmental efficiency of the proposed system. Conventional breakwaters are materially intensive and ecologically invasive. The modularity, reduced mass, and reversibility of the prototypes presented here open a path toward a new generation of eco-technical infrastructures deployable, maintainable, and compatible with nature-based solutions. As Davis et al. (2006) note in the context of San Diego Bay, the removal of rigid dams to restore tidal marshes can achieve erosion control while fostering habitat regeneration.

Integrating such bio-inspired components with soft engineering strategies such as beach drainage systems (Damiani et al., 2009) could significantly reduce the ecological cost of wave control structures, while expanding their functionality and responsiveness.

Importantly, the results of this experimental phase provided the empirical foundation for the development of a patentable invention, which received a positive international search report on all three evaluative criteria. Yet as Cocco (1985, p. 151) reminds us:

"Invention is the idea of practical interest, which can normally be patented; it is essentially the product of theoretical activity."

This project does not aim merely to produce a form, but to frame a new epistemology of infrastructure one in which performance is not just structural, but ecological and systemic. A model not of resistance, but of resonance with the living fluidity of the marine environment

Conclusions: Toward a New Culture of Coastal Design

This study explores the development of bio-inspired models for coastal protection, from the initial literature review and conceptual design to prototyping, testing, and evaluation. Through this trajectory, the project sought to contribute meaningfully to the field of design-led solutions for shoreline defense, assessing their effectiveness in terms of wave energy attenuation, environmental impact reduction, and potential for integration into sustainable and socially accepted infrastructures.

The exploration of multifunctional coastal protection systems at the intersection of industrial design, marine biology, and coastal engineering, represents a frontier where ecological logic and technological invention converge. The results offer tangible evidence that a nature-inspired design approach can rival, and in some cases outperform, conventional rock breakwaters not only in hydrodynamic efficiency but also in adaptability, volume reduction, and potential for ecological integration.

The comparative performance of the tested prototypes is significant. The T-Type model consistently yielded the lowest wave transmission coefficients (Kt), demonstrating an effective capacity to dissipate energy under both regular and storm wave conditions. Its rotated variant (rT-Type), while slightly less efficient, still performed markedly better than baseline geometries. In contrast, the HT-Type and rHT-Type models revealed limitations, likely due to interference generated by their upper cap elements—raising important questions about how additional volumetric features impact flow behavior. The C-Type, serving as cylindrical control, and the L-Type, with leaf-like biomorphic geometry, showed consistent and predictable behavior but lower energy attenuation.

These findings underscore the potential of bio-inspired geometries not only as experimental artifacts but as prototypes for patentable systems. The models served as the foundation for an industrial invention that has received positive evaluation across all patentability criteria demonstrating the compatibility of design research with innovation-driven processes.

However, invention here is not understood exclusively as novelty or technological optimisation. Design should also be understood as a creative act of invention, a form of theoretical and practical activity that identifies emerging needs and reconfigures the relationships between form, function and performance of materials (Buono M. 2018). This project has embraced this philosophy, prioritising original thinking, ecological intelligence and process-based innovation.

The integration of parametric design, additive manufacturing, and experimental testing proved essential in bridging abstract biomimetic principles with engineered realities. Through this process, complex natural behaviors such as turbulence modulation, sediment interaction, and permeability regulation, were translated into tangible morphologies, revealing a new language of form that is neither ornamental nor rigidly technical, but performative.

Compared to traditional breakwaters, bio-inspired systems show clear advantages in spatial economy, reversibility, and environmental compatibility. Their permeable structure supports natural flows, helping to avoid anoxic stagnation while allowing for seasonal adaptability. Such systems may also be combined with other soft protection strategies, as suggested by Levy et al. (2022) and Damiani et al. (2009), creating hybrid approaches where wave energy is absorbed offshore while beach health and sediment transport are preserved.

Importantly, a preliminary model has been proposed to correlate average Kt values with prototype geometry and surface friction mechanisms, offering a first step toward predictive modeling of future systems. This could inform the macroscale design of bio-integrated infrastructures, tailored to local hydrodynamics and ecological conditions.

However, further refinement particularly in terms of ultrastructural analysis, material composition, and biotic compatibility, will be needed to translate laboratory insight into real-world applications.

The work demonstrates that multifunctional, bio-inspired structures can serve as catalysts for a new culture of coastal engineering one did not root in resistance, but in resonance with the systems it seeks to protect. It affirms the power of design not merely as a mode of making, but as a tool for reimagining how human interventions relate to the planetary scale.

In conclusion, a nature-based design philosophy offers a promising paradigm shift. It suggests a future in which coastal defenses are no longer imposed upon ecosystems, but emerge from within them, shaped by their rhythms, informed by their intelligence, and integrated into their complexity. This vision demands more than technical acumen; it requires collaborative action, inclusive planning, and a political will attuned to long-term resilience.

As we confront increasing uncertainty and ecological vulnerability, design must reassert its role not as a passive responder, but as a proactive agent of transformation. The protection of coastlines, like the regeneration of life itself, must become a shared project, capable of blending innovation with care, structure with adaptation, and vision with responsibility.

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Source of funding
This work has not received any funding.