

## Biomimicry-Based Design Strategies for Advanced Marine Aquaculture Cage Systems: A Review

Mariammal Senthilvel\*<sup>1</sup>, Dr.J.Jaculine Pereira<sup>2</sup>, Dr.R.Somu Sunder Lingam<sup>3</sup>,  
Dr. A.Anix Vivek Santhiya<sup>4</sup>

Tamil Nadu Dr J Jayalalitha Fisheries University, Nagapattinam, Tamil Nadu -  
611002

Corresponding author mail id: mariyae008@gmail.com

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### Abstract

The rapid expansion of marine aquaculture is essential for meeting the growing global demand for seafood within the framework of the Blue Economy. However, conventional aquaculture cage systems face significant challenges in offshore environments, including strong hydrodynamic forces, biofouling, structural fatigue, predator interactions, and environmental impacts from nutrient accumulation. These challenges highlight the need for innovative engineering approaches that improve cage performance while maintaining environmental sustainability. Biomimicry, defined as the practice of emulating nature's time-tested strategies to solve human design challenges, offers promising solutions for developing resilient and efficient aquaculture infrastructure. This article explores how biological systems can inspire the design of next-generation marine aquaculture cages. Structural principles derived from deep-sea sponges (*Euplectella aspergillum*) demonstrate how hierarchical lattice architectures can enhance strength and stability under hydrodynamic loading. Shark skin dermal denticles provide insights for antifouling surfaces that reduce biofilm attachment and maintenance requirements. Flexible macroalgae such as kelp illustrate strategies for wave-resistant structures capable of adapting to dynamic ocean conditions. Hydrodynamic efficiency observed in schooling fish suggests optimized cage geometries that reduce drag and improve water circulation. Additionally, defensive mechanisms in porcupinefish inspire predator-resistant cage structures, while coral and mollusk biomineralization processes inform the development of self-healing materials for improved infrastructure durability. Beyond structural innovations, ecosystem-inspired approaches such as Integrated Multi-Trophic Aquaculture (IMTA) mimic coral reef nutrient cycling to reduce environmental impacts, while sensory systems like the fish lateral line inspire smart monitoring technologies for real-time cage management. Together, these biomimetic strategies highlight the potential of integrating biological principles with modern engineering, advanced materials, and artificial intelligence to enhance aquaculture system performance. By translating natural design strategies into aquaculture engineering solutions, biomimicry can contribute to the development of sustainable, resilient, and efficient offshore aquaculture systems, supporting global seafood production while minimizing environmental impacts. Such innovations are expected to play a critical role in advancing sustainable marine food systems and strengthening the long-term viability of the Blue Economy.

**Keywords:** Biomimicry, Aquaculture cages, Hydrodynamics, Biofouling, Sustainable aquaculture

## Introduction

Aquaculture has emerged as a critical component of global food systems, playing a significant role in ensuring food and nutrition security. Aquatic food systems are increasingly recognized for their capacity to provide affordable, nutrient-rich food to a growing global population. In 2022, global fisheries and aquaculture production reached a record 223.2 million tonnes, with aquaculture contributing more than 57% of aquatic animal products for human consumption (FAO, 2024). Biofouling is a major challenge in marine aquaculture, where the accumulation of diverse fouling organisms on culture systems and infrastructure significantly affects production efficiency. In finfish cage systems, biofouling primarily impacts infrastructure by restricting water exchange, increasing disease susceptibility, and causing structural deformation of cages. The economic burden of biofouling is considerable, accounting for approximately 5–10% of total production costs, thereby emphasizing the need for effective and sustainable antifouling strategies (Fitridge et al., 2012). Surface-based marine cage systems are highly exposed to hydrodynamic forces such as waves, currents, and extreme weather events, which can compromise cage stability and fish welfare. Submerged cage technologies have been proposed to mitigate these hydrodynamic challenges; however, they introduce biological constraints related to buoyancy regulation, particularly in species with open swim bladders. Although innovations such as underwater air domes have improved submerged cage functionality, further research is required to optimize environmental conditions and ensure consistent growth and welfare across production cycles (Sievers et al., 2022). Net biofouling significantly reduces water flow within fish cages, leading to diminished water exchange and deterioration of culture conditions (Madin et al., 2010). Reduced flow velocities inside cages ( $<10 \text{ cm s}^{-1}$ ) promote rapid accumulation of fouling organisms, whereas higher external flow rates help limit fouling development (Madin et al., 2010). Furthermore, cage farming activities, particularly feed inputs, can substantially increase biofouling intensity, emphasizing the need for optimized cage design to maintain adequate hydrodynamic conditions (Madin et al., 2010). Sustainable aquaculture development requires reducing dependence on fishmeal and fish oil derived from wild stocks, as their continued use poses significant ecological and food security concerns (Allsopp et al., 2013). The adoption of integrated and low-trophic-level aquaculture systems is increasingly recognized as an effective strategy to enhance environmental sustainability and optimize resource utilization in aquaculture practices (Allsopp et al., 2013). Innovative approaches such as recirculating aquaculture systems and the use of alternative, sustainable feed sources are essential to minimize environmental impacts and improve the long-term viability of aquaculture production systems (Allsopp et al., 2013). Marine biofouling

remains a major challenge in aquatic systems, significantly affecting the performance and durability of marine structures, including aquaculture cages (Kumar et al., 2021). Conventional biocide-based antifouling methods, although effective, pose serious environmental risks, thereby necessitating the development of eco-friendly and sustainable alternatives (Kumar et al., 2021). Biomimetic approaches, inspired by natural antifouling mechanisms such as surface microstructures, have emerged as promising strategies for developing environmentally benign antifouling technologies in marine applications (Kumar et al., 2021).

### Concept of Biomimicry

Biomimicry is an interdisciplinary approach that involves learning from and emulating nature's designs, processes, and systems to solve complex engineering problems in a sustainable manner (Vincent et al., 2006). It integrates principles from biology, engineering, and material science to develop innovative solutions that are efficient, adaptive, and environmentally compatible (Bhushan, 2009).

Biomimicry can be broadly classified into three levels: form, process, and system. At the form level, biomimicry focuses on replicating the physical structures and morphological features of biological organisms to improve engineering design. For instance, streamlined shapes inspired by fish bodies have been applied to enhance hydrodynamic efficiency in marine structures (Bhushan, 2009).

At the process level, biomimicry involves mimicking biological mechanisms and functional strategies observed in nature. This includes the replication of natural processes such as self-cleaning, adhesion, and antifouling properties, as seen in shark skin-inspired surfaces that reduce biofouling in marine environments (Kumar et al., 2021).

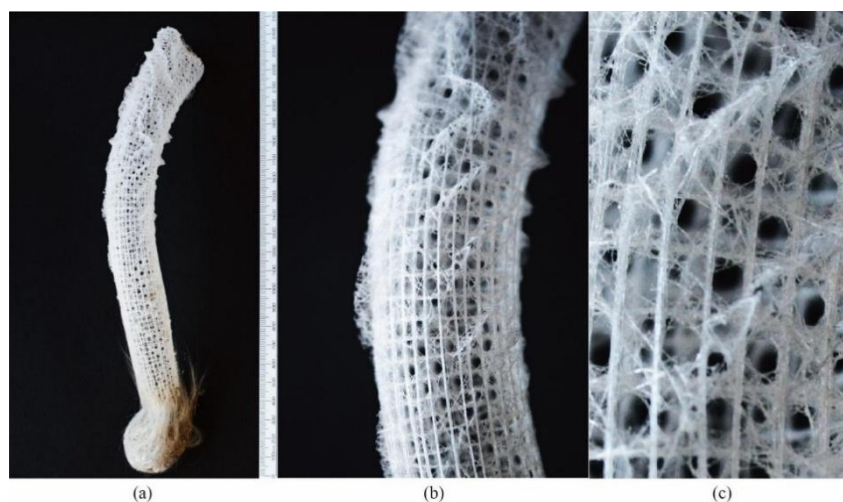
At the system level, biomimicry emphasizes the imitation of ecological interactions and natural system dynamics to achieve sustainability. This approach considers the integration of multiple components working synergistically, similar to natural ecosystems, to optimize resource use and minimize environmental impact (Bar-Cohen, 2016).

### Structural Strength and Stability Inspired by Deep-Sea Sponges

#### Biological Inspiration: *Euplectella aspergillum* (Venus Flower Basket Sponge)

The deep-sea sponge *Euplectella aspergillum*, commonly known as the Venus Flower Basket, exhibits a remarkable skeletal architecture composed of silica spicules arranged in a highly ordered hierarchical lattice structure. This lattice consists of longitudinal, transverse, and diagonal elements that create a cylindrical grid capable of distributing mechanical loads efficiently while maintaining structural rigidity. The hierarchical organization of the sponge skeleton enhances both stiffness and toughness by allowing stresses to be transferred across

multiple structural levels, from nanoscale silica fibers to the macroscopic lattice framework [Aizenberg et al., 2005; Weaver et al., 2010]. Such structural strategies enable the sponge to maintain mechanical stability under deep-sea environmental forces, including water movement and mechanical loading.



**Fig. 1. The skeletal system of the *Euplectella aspergillum*, showing: (a) the entire skeletal tube, (b) a magnified view highlighting its regular lattice-like structure, and (c) the detailed pattern of alternating open and closed cells. Credit: *Composite Structures* (2024). Adapted from (Ramakrishna & Bala Murali, 2023).**

### Engineering Problem: Structural Stress in Offshore Aquaculture Cages

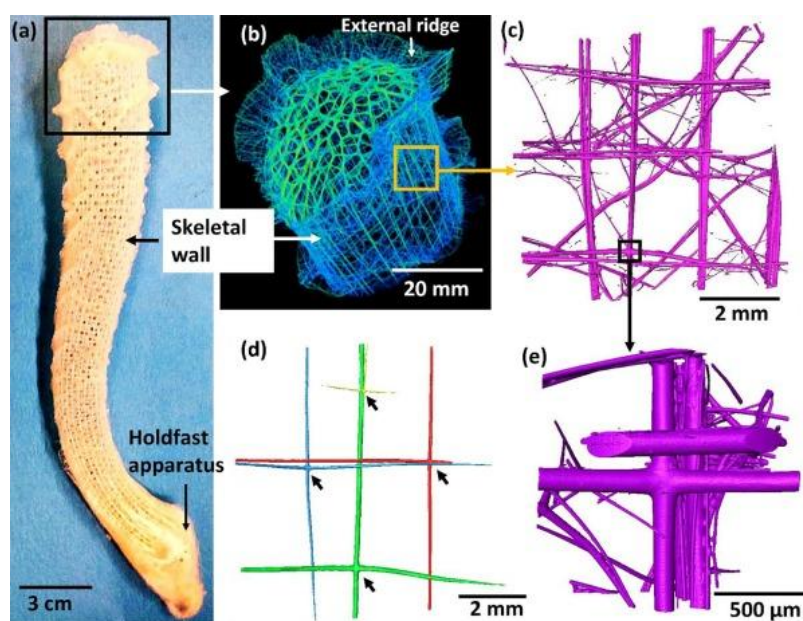
Marine aquaculture cages deployed in offshore environments are subjected to significant hydrodynamic forces from waves and currents, which can induce high stresses on cage frames and mooring systems. These forces can cause deformation, oscillation, and structural instability in cage structures, particularly during high-energy ocean conditions [Fredriksson et al., 2003]. In addition to instantaneous loading, repeated wave-induced motion results in cyclic mechanical loading, which contributes to structural fatigue and material degradation over time in aquaculture infrastructure [Lader et al., 2008]. Consequently, there is a growing need for structural designs that can effectively distribute loads and improve resilience in offshore aquaculture systems.

### Biomimetic Engineering Solution: Sponge-Inspired Lattice Structures

The skeletal architecture of *Euplectella aspergillum* provides valuable design insights for developing lightweight yet mechanically robust structural frameworks. The sponge's lattice geometry demonstrates how hierarchical structural organization can enhance stiffness and load distribution while minimizing material usage [Aizenberg et al., 2005]. Engineers and materials

scientists have increasingly studied such biological architectures to develop biomimetic lattice materials and frameworks capable of achieving high strength-to-weight ratios and improved mechanical performance [Fratzl & Barth, 2009].

Advances in manufacturing technologies, particularly additive manufacturing (3D printing) and composite material engineering, now enable the fabrication of complex lattice structures inspired by biological architectures. These technologies allow engineers to replicate hierarchical geometries similar to those observed in sponge skeletons, thereby creating structural frameworks with enhanced load distribution and structural stability [Meyers et al., 2008].



**Fig. 2. Multiscale hierarchical structure of *E. aspergillum* investigated by x-ray microtomography-** (a) photograph of *E. aspergillum*'s skeleton, (b) Volume rendering showing the upper section of *E. aspergillum*, (c) volume rendering showing a small portion of the skeletal wall, (d) cross-shaped spicules segmented and represented using different colors, arrows show nodes that contain axial center of spicules (e) volume rendering showing the axial center and cross shape (four rays) of spicule. Adapted from (Morankar et al., 2023).

## Anti-Biofouling Surfaces Inspired by Shark Skin

### Biological Inspiration: Shark Skin and Dermal Denticles

Sharks possess a unique skin structure composed of microscopic tooth-like scales known as dermal denticles. These denticles form riblet-like surface patterns aligned along the body of the shark, producing a textured microtopography that reduces hydrodynamic drag and inhibits the attachment of fouling organisms. The geometry of these riblets alters the boundary

layer of water flow across the skin surface, thereby limiting the ability of microorganisms and larvae to settle and adhere [Bechert et al.,1997; Schumacher et al., 2007].

Research in biomimetic materials has demonstrated that the microstructured topography of shark skin can significantly reduce the attachment of bacteria, algae, and other fouling organisms. These natural antifouling properties have inspired the development of engineered surfaces that mimic dermal denticle patterns for applications in marine coatings and biomedical devices [Schumacher et al., 2007; Chung et al., 2007].

### **Engineering Problem: Biofouling in Marine Aquaculture Cages**

Biofouling is one of the most persistent operational challenges in marine aquaculture systems. Cage nets submerged in seawater rapidly become colonized by fouling organisms such as barnacles, algae, hydroids, and mussels, forming dense biological layers on net surfaces. The accumulation of these organisms reduces net permeability and restricts water exchange within the cage, which can negatively affect oxygen availability and fish health [Fitridge et al., 2012].

In addition to reducing water flow, biofouling increases the hydrodynamic drag acting on cage structures, placing greater stress on cage frames and mooring systems. Fouled nets also require frequent cleaning or replacement, resulting in increased operational costs and labor requirements. Furthermore, conventional antifouling treatments often rely on chemical coatings that may release biocides into the marine environment, raising ecological concerns regarding their long-term sustainability [Fitridge et al., 2012; Schultz et al., 2011].

### **Biomimetic Engineering Solution: Shark-Skin-Inspired Riblet Surfaces**

The antifouling properties of shark skin have inspired the development of microstructured riblet surfaces that replicate the geometry of dermal denticles. These surfaces function by disrupting microbial attachment and reducing the effective contact area available for settlement. Studies have shown that engineered surfaces mimicking shark skin microtopography can significantly inhibit bacterial colonization and biofilm formation without the use of toxic chemical coatings [Schumacher et al., 2007; Chung et al., 2007].

Advances in materials engineering now enable the fabrication of such microstructures using technologies such as laser etching, micro-molding, and advanced polymer manufacturing. These techniques allow the precise replication of riblet geometries that mimic shark skin patterns at micro- and nanoscale levels.

### **Flexible Wave-Resistant Structures Inspired by Seaweed**

#### **Biological Inspiration: Kelp Forests and Flexible Macroalgae**

Large marine macroalgae, particularly kelp species such as *Macrocystis pyrifera* and

*Laminaria* spp., exhibit remarkable flexibility that enables them to survive in highly energetic coastal environments. These organisms possess elongated, flexible stipes and blades that allow them to bend and reorient in response to water movement rather than resisting hydrodynamic forces. This mechanical strategy reduces the drag forces acting on the algae by allowing them to streamline with water flow, thereby minimizing structural stress and preventing breakage under strong wave action [Koehl, 1984; Denny & Gaylord, 2002].

The mechanical behavior of kelp is therefore a classic example of passive reconfiguration, where biological structures deform in response to fluid forces to reduce hydrodynamic loading. This adaptation allows kelp forests to persist in wave-exposed environments where rigid structures would experience significantly higher stress and potential failure.

### **Engineering Problem: Structural Damage to Rigid Aquaculture Cages**

Marine aquaculture cages deployed in offshore or exposed coastal locations are frequently subjected to strong waves, currents, and storm events. Traditional cage systems constructed from rigid materials such as steel or high-density polyethylene (HDPE) frames can experience significant mechanical stress when exposed to these hydrodynamic forces. Under extreme conditions, rigid structures may deform, suffer structural fatigue, or even fail, resulting in equipment damage and fish escape events [Fredriksson et al., 2003; Lader et al., 2008].

As aquaculture operations expand into more energetic offshore environments, there is increasing interest in developing cage structures that can adapt dynamically to water movement, thereby reducing the structural loads imposed by waves and currents.

### **Biomimetic Engineering Solution: Flexibility-Based Structural Design**

The mechanical strategy observed in kelp provides an important design principle for marine engineering: structures that can flex and reorient in response to fluid forces experience lower hydrodynamic loads compared to rigid structures. By allowing controlled deformation, flexible systems can dissipate wave energy and reduce stress concentrations within structural components [Denny & Gaylord, 2002].

Applying this principle to aquaculture cage design suggests the development of flexible or semi-flexible cage systems capable of adapting to dynamic ocean conditions. Instead of resisting wave forces entirely, these biomimetic systems would partially move with the surrounding water, thereby lowering mechanical stress.

### **Hydrodynamic Efficiency Inspired by Fish Schools**

#### **Biological Inspiration: Hydrodynamics of Schooling Fish**

Many fish species exhibit schooling behavior, where individuals swim in coordinated

groups that maintain specific spatial arrangements. This behavior provides hydrodynamic advantages because the vortices generated by one fish can be exploited by neighboring fish, reducing the energy required for swimming. Research has shown that fish swimming in organized schools can experience improved propulsion efficiency and reduced drag compared with solitary swimming [Weihs, 1973; Liao, 2007].

In such formations, the spacing and orientation between individuals allow fish to take advantage of the wake structures generated by others, a mechanism often referred to as hydrodynamic drafting. By optimizing their position relative to surrounding individuals, fish can reduce the energetic cost of locomotion while maintaining stability in moving water [Weihs, 1973]. These fluid dynamic interactions have attracted considerable interest in engineering because they demonstrate how spatial arrangement and flow alignment can improve hydrodynamic efficiency.

### **Engineering Problem: Drag Forces on Aquaculture Cage Systems**

Aquaculture cages deployed in marine environments are constantly exposed to water currents and wave-induced flows, which generate hydrodynamic drag on cage structures and nets. Increased drag forces can lead to deformation of nets, increased tension on mooring systems, and higher structural loads on cage frames. These forces may also increase the energy required to maintain cage stability and positioning in offshore environments [Lader et al., 2008].

In addition, poorly designed cage geometries can disrupt natural water flow patterns around the structure, increasing turbulence and resistance. Such inefficiencies may reduce water exchange within the cage and increase mechanical stress on infrastructure components [Fredriksson et al., 2003].

### **Biomimetic Engineering Solution: Schooling-Inspired Spatial Optimization**

The hydrodynamic advantages observed in schooling fish provide an important design principle for marine infrastructure: efficient spatial arrangement and streamlined shapes can reduce drag forces in fluid environments. Engineers can apply this concept to aquaculture cage design by optimizing the geometry and layout of cage structures to interact more efficiently with surrounding water flow.

Hydrodynamic modeling studies have demonstrated that streamlined structures experience significantly lower drag compared with blunt or irregular shapes, suggesting that cage geometry plays a critical role in determining flow behavior around aquaculture systems [Lader et al., 2008].

### **Predator Protection Inspired by Porcupine Fish Defense**

## **Biological Inspiration: Defensive Structures of Porcupinefish**

Porcupinefishes belonging to the family Diodontidae possess a highly effective defense mechanism against predators. When threatened, these fish rapidly inflate their bodies by ingesting water or air, causing their bodies to expand and exposing numerous rigid dermal spines that cover their skin. This inflation transforms the fish into a larger, spiny structure that is difficult for predators to grasp or swallow. The spines function as a mechanical deterrent, discouraging attacks from predators such as large fishes and marine mammals [Leis, 2006; Randall et al., 1997].

## **Engineering Problem: Predator Interactions with Aquaculture Cages**

Predator interactions are a significant challenge in marine aquaculture operations. Large marine predators such as sharks, seals, and sea lions may attempt to access cultured fish within cage systems. These interactions often involve biting, tearing, or deforming cage nets, which can lead to structural damage, fish escape events, and economic losses for aquaculture producers [Nash et al., 2005; Sanchez-Jerez et al., 2016].

In addition to direct structural damage, predator attacks can also induce stress responses in cultured fish, negatively affecting growth, health, and overall production performance. Consequently, the development of cage designs that provide effective predator deterrence and structural protection remains an important engineering objective in aquaculture infrastructure. Biomimetic Engineering Solution: Spine-Inspired Protective Systems

The defensive strategy of porcupinefish suggests a biomimetic approach to predator protection based on physical deterrence through structural protrusions. By creating cage systems that incorporate external protective elements analogous to the spines of porcupinefish, aquaculture infrastructure can reduce the likelihood of predator attacks and net damage.

Biomimetic design principles emphasize the use of passive mechanical barriers that discourage predator interaction without harming wildlife or relying on active deterrent systems.

## **Self-Healing Materials Inspired by Coral and Shell Repair**

### **Biological Inspiration: Coral Skeleton Repair and Mollusk Shell Regeneration**

Many marine organisms possess the ability to repair structural damage through biological mineralization processes. Reef-building corals can regenerate damaged skeletal structures by depositing calcium carbonate through specialized cells that rebuild the skeletal matrix following injury [Allemand et al., 2011]. Similarly, mollusks such as oysters and mussels can repair damaged shells through biomineralization processes in which the mantle secretes calcium carbonate layers to restore structural integrity [Mount et al., 2004].

These natural repair mechanisms demonstrate how biological systems maintain

durability in physically demanding marine environments through continuous self-maintenance and regeneration, offering inspiration for the development of self-healing materials in engineering applications.

### **Engineering Problem: Structural Degradation in Aquaculture Cage Materials**

Aquaculture cage systems are continuously exposed to mechanical stress, corrosion, and environmental wear caused by waves, currents, and operational handling. Over time, cage nets and structural components can develop micro-cracks, abrasion damage, and material fatigue, which may reduce structural strength and increase the risk of failure [Lader et al., 2008]. Maintenance and replacement of damaged nets represent significant operational costs in aquaculture systems.

### **Biomimetic Engineering Solution: Self-Healing Materials**

Inspired by biological repair processes, materials scientists have developed self-healing polymers that can automatically repair micro-scale damage. These materials typically incorporate microcapsules or reversible chemical bonds that activate when cracks form, allowing the material to restore its mechanical integrity [White et al., 2001; Hager et al., 2010].

### **Eco-Integrated Cage Systems Inspired by Coral Reef Ecosystems**

#### **Biological Inspiration: Coral Reef Ecosystems**

Coral reefs represent one of the most efficient nutrient-cycling ecosystems in the marine environment. Despite existing in nutrient-poor waters, reef ecosystems maintain high productivity through complex biological interactions among multiple trophic levels, including corals, algae, mollusks, and microorganisms [Moberg & Folke, 1999]. These organisms form interconnected systems where nutrients are continuously recycled, supporting ecosystem stability and productivity.

#### **Engineering Problem: Nutrient Pollution from Aquaculture**

Intensive aquaculture systems can release excess nutrients such as nitrogen and phosphorus into surrounding waters through uneaten feed and fish waste. These nutrient inputs may lead to localized eutrophication, algal blooms, and environmental degradation if not properly managed [Troell et al., 2009].

#### **Conclusion**

Biomimicry provides powerful solutions for designing next-generation marine aquaculture cages. By learning from marine organisms such as sponges, sharks, seaweed, fish, and corals, engineers can create systems that are stronger, more efficient, and environmentally sustainable. Integrating these nature-inspired innovations will play a crucial role in advancing

the Blue Economy and sustainable aquaculture development.

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