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LONG-TERM ECOLOGICAL FUNCTIONALITY OF POROUS ARTIFICIAL REEF STRUCTURES FOR MACROALGAL BED RESTORATION IN OLIGOTROPHIC COASTAL WATERS

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ABSTRACT: Seaweed bed ecosystems in semi-enclosed coastal seas such as the Seto Inland Sea have experienced significant degradation due to land reclamation, oligotrophication, and rising sea temperatures. To address these challenges, we developed and field-tested porous artificial reef structures (Marine Mash) designed to promote macroalgal colonization and associated ecosystem functions under nutrient-limited conditions. Long-term monitoring (>13 years) at two coastal sites evaluated three ecological functions: prey organism biomass on porous substrates, macroalgal growth, and epiphytic community development. Porous substrates supported significantly higher biomass of preferred prey organisms compared with stone, concrete, and steel controls (F=161, p<0.01), while the Marine Mash structure promoted greater macroalgal biomass than stone reefs (t (12) =12.475, p=3.16×10^{-8}) and enhanced epiphytic organism biomass on algal surfaces (t (9) =9.3, p=6.51×10^{-6}). These results suggest that the integrated structural design—combining hydrodynamic sediment control via the sloped roof geometry, microhabitat complexity within the graded porous substrate (mean particle diameter 5 mm, void ratio 25%), and strategic deployment on sandy mud substrate to minimize sea urchin grazing—may foster multiple trophic functions simultaneously, offering a potentially scalable Nature-based Solution for oligotrophic coastal restoration.

Keywords: Seaweed bed, Seto Inland Sea, Coastal ecosystem, Porous material

1. INTRODUCTION

In the context of global climate change mitigation, increasing attention has been directed to blue carbon, which refers to the carbon sequestration capacity of marine ecosystems such as mangroves, seagrass meadows, and seaweed beds [1, 2]. Compared to terrestrial green carbon ecosystems, blue carbon ecosystems exhibit a three- to ten-fold higher CO_2 absorption capacity per unit area [3], together with the potential for long-term carbon storage in biomass and sediments [4]. Despite their ecological and climatic significance, coastal vegetated ecosystems worldwide are increasingly threatened by anthropogenic coastal development, altered nutrient regimes, and climate change impacts [5]. In particular, temperate seaweed beds have shown marked declines in many regions, including the Seto Inland Sea of Japan, where substantial degradation of seaweed beds has been widely reported in recent decades [6, 7].

Globally, a wide range of restoration and enhancement technologies have been developed to address the loss of macroalgal and other vegetated coastal habitats. In North America and other regions, artificial reef systems such as Reef Ball® have been widely deployed, primarily to provide hard substrates for algal attachment and to increase habitat complexity. In Europe, restoration efforts have focused largely on seagrass ecosystems, which generally require stable sedimentary environments and favorable light conditions for successful recovery. In East Asia, including Japan, artificial seaweed beds and block-type reefs have been installed to compensate for the loss of natural rocky substrates. However, most existing approaches emphasize attachment success or initial colonization, and their effectiveness is often evaluated over relatively short time scales. Quantitative assessments of broader ecosystem functions—such as prey organism production, epibiotic community development, and food-web enhancement—under long-term field conditions remain limited [8,9].

The Seto Inland Sea provides a representative and increasingly important case study for examining the limitations of conventional algal bed restoration strategies. Following severe eutrophication during the mid-twentieth century, strict nutrient load reduction policies were implemented to improve water quality. Although these measures successfully reduced red tide occurrences and improved water transparency, they also resulted in progressive oligotrophication in several coastal areas. Consequently, primary productivity and associated food-web functions have not fully recovered, and declines in seaweed beds and benthic organisms have been observed even under improved water clarity conditions [5–7]. This paradox of a "clean but unproductive sea" highlights the need for restoration technologies that can function effectively under nutrient-limited environments, where the provision of attachment substrates alone may be insufficient to restore ecosystem functions.

In response to these challenges, structure-based restoration approaches that integrate physical design with ecological functionality have gained increasing attention. Porous materials, in particular, are expected to enhance habitat complexity, modify near-bottom hydrodynamic conditions, and promote the retention and production of organic matter and microorganisms that serve as food resources for higher trophic levels [8,9,10]. Although the biocompatibility of porous materials and their potential to enhance biological colonization have been documented in previous studies [11,12], few investigations have quantitatively evaluated how porous algal bed creation structures contribute simultaneously to multiple ecosystem functions, including macroalgal growth, prey organism biomass, and epibiotic organism colonization. Moreover, empirical evidence based on long-term field observations under oligotrophic coastal conditions remains scarce.

This study addresses these gaps by evaluating the ecological functionality of seaweed bed creation reefs utilizing porous materials, hereafter referred to as Marine Mash, developed at Kagawa University. The structural design also draws inspiration from research on specialized shelters for juvenile fish, which demonstrated that providing physical refugia is essential for enhancing recruitment [13]. Recent advancements in porous substrate technology at the same institution also include the development of functional materials such as hydroxyapatite-mixed porous concrete [14]. Based on long-term field observations spanning more than a decade in the Seto Inland Sea, this study quantitatively assesses (i) the establishment and persistence of seaweed beds, (ii) the biomass and composition of prey organisms associated with the structures, and (iii) the development of epibiotic communities on porous substrates. By focusing on ecosystem functions rather than attachment success alone, this research aims to provide a comprehensive evaluation of porous seaweed bed creation structures applicable to nutrient-limited and enclosed coastal seas.

The remainder of this paper is organized as follows. Section 2 outlines the significance of the study and the conceptual framework of functional seaweed bed restoration. Section 3 describes the study area, the design of the porous structures, and the methods used for biological and environmental surveys. Section 4 presents the results of macroalgal development, prey organism biomass, and epibiotic community structure. Section 5 discusses the ecological implications of the findings in comparison with existing restoration technologies. Finally, Section 6 summarizes the main conclusions and highlights future challenges for the application of porous seaweed bed creation structures in enclosed coastal environments.

1.1 Global Context of Seaweed Bed Restoration Technologies

Globally, a wide range of technologies has been developed for the restoration of coastal vegetated ecosystems; however, their target ecosystems, design philosophies, and functional priorities differ considerably, and no unified technological framework has yet been established.

In the United States, the Reef Ball system, originally developed in the 1990s, has been widely deployed in more than 70 countries. Reef Ball structures are spherical, porous artificial reefs designed primarily to provide attachment surfaces and habitat complexity for corals and sessile invertebrates. While their effectiveness as hard substrates have been demonstrated, their capacity to sustain seaweed beds and associated trophic support functions under nutrient-limited conditions has not been sufficiently verified.

In Europe, particularly in the Netherlands and the United Kingdom, restoration technologies have focused predominantly on seagrass (e.g., *Zostera* spp.). Seagrass ecosystems are highly valued as blue carbon sinks because they transfer organic carbon directly into sediments through their root systems. However, seagrass restoration requires stable sediments and high-water transparency. In dynamic and turbid environments such as the Seto Inland Sea, large-scale recovery of seagrass meadows has proven extremely challenging, and historical declines have not yet been reversed.

In East Asia, including Japan, Korea, and China, artificial seaweed bed technologies targeting large macroalgae (e.g., *Sargassum* spp. and kelps) have been developed over several decades. These approaches typically involve the deployment of concrete blocks or natural stones to increase available attachment area. Nevertheless, most existing designs prioritize surface area expansion alone, and quantitative evaluations of food provisioning, higher trophic support, and long-term persistence under oligotrophic conditions remain limited.

More recently, seagrass restoration programs integrating advanced monitoring technologies have been initiated by agencies such as NASA and NOAA in the United States. For example, pilot projects in the Indian River Lagoon combine biodegradable materials, transplantation techniques, and remote sensing. While innovative, these approaches are species-specific and rely heavily on active transplantation, which differs fundamentally from structure-driven, self-organizing ecosystem formation.

In Australia, initiatives such as Kelp Forest restoration projects have integrated science with social engagement, including the use of artistically designed structures to mitigate grazing pressure and raise public awareness of kelp loss. Although these efforts are highly effective in enhancing societal recognition of coastal degradation, quantitative assessments of ecosystem functions such as food-web support and carbon sequestration remain limited.

Against this global backdrop, Marine Mash occupies a distinctive and unique position as an integrated macroalgal restoration technology designed specifically for semi-enclosed, nutrient-limited coastal seas. Unlike conventional approaches that depend primarily on nutrient availability or transplantation, Marine Mash has demonstrated sustained functionality over more than a decade under oligotrophic conditions in the Seto Inland Sea. Its design integrates structural, hydrodynamic, and ecological principles, enabling the structure to function not merely as an attachment surface but as an engineered device that actively fosters ecosystem formation and persistence.

1.2 Research gaps, originality, and contributions of this study

Despite the wide range of coastal restoration technologies developed worldwide, several critical research gaps remain, particularly with respect to seaweed bed restoration in semi-enclosed and nutrient-limited seas. First, many existing approaches implicitly assume that sufficient nutrient availability is a prerequisite for successful restoration. Consequently, their applicability under oligotrophic conditions—where nutrient inputs are deliberately reduced for water quality management—has remains largely unverified through long-term field data.

Second, the evaluation of artificial reef and algal bed creation technologies has often been limited to single indicators, such as algal coverage or biomass. While these metrics are important, they do not adequately capture broader ecosystem services, including food provisioning for higher trophic levels, enhancement of biodiversity, and contributions to climate change mitigation through carbon sequestration. Consequently, the multifunctional nature of restored macroalgal ecosystems remains insufficiently quantified.

Third, most previous studies have relied on short-term monitoring periods, typically ranging from one to three years. Such time frames are often insufficient to assess ecosystem persistence, resilience to environmental variability, and the risk of post-restoration decline. Long-term empirical evidence demonstrating sustained functionality is therefore critically lacking.

In this context, the present study addresses these gaps through a comprehensive, long-term evaluation of Marine Mash, an artificial seaweed bed creation structure developed at Kagawa University. The originality of this study lies in three key aspects. First, it demonstrates that sustained seaweed bed formation and associated ecosystem functions can be achieved under oligotrophic conditions without direct nutrient enrichment or repeated transplantation. Second, it quantitatively evaluates multiple ecosystem services—including macroalgal production, food provisioning via epibiotic and benthic organisms, and carbon dioxide sequestration—within a unified analytical framework. Third, it is based on continuous field observations spanning more than 13 years, providing rare empirical evidence of long-term stability and functionality.

Based on these features, this study contributes not only to the scientific understanding of macroalgal ecosystem restoration but also to the development of practical Nature-based Solutions (NbS) for semi-enclosed coastal seas. The findings provide a transferable knowledge base for regions worldwide that face similar challenges, including nutrient management constraints, habitat degradation, and the need for climate change mitigation and adaptation.

2. RESEARCH SIGNIFICANCE

This study presents a structure-based approach to restoring macroalgal habitats in oligotrophic coastal waters using porous artificial reef structures (Marine Mash). The novelty lies in demonstrating that sustained macroalgal productivity and trophic functions can be maintained without nutrient enrichment, supported by more than 13 years of field observations in the Seto Inland Sea. The originality lies in integrating porous substrate design, hydrodynamic sediment control, and habitat complexity to enhance ecosystem functions under nutrient-limited conditions. These results provide rare long-term empirical evidence that structural habitat design can enhance coastal ecosystem productivity and support scalable nature-based solutions.

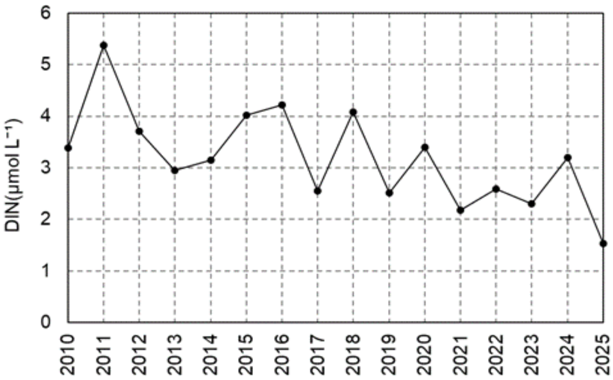

Fig. 1 Long-term variation of dissolved inorganic nitrogen (DIN) in offshore waters of Kagawa Prefecture (2010–2025). Data source: Kagawa Prefectural Fisheries Experimental Station monitoring program.

3. MATERIALS AND METHODS

3.1 Experimental Sites

Field experiments were conducted at two coastal sites near Kamano Fishing Port and Shinoo Fishing Port, both situated in Ajicho, Takamatsu City, Kagawa Prefecture, Japan (Fig. 1).

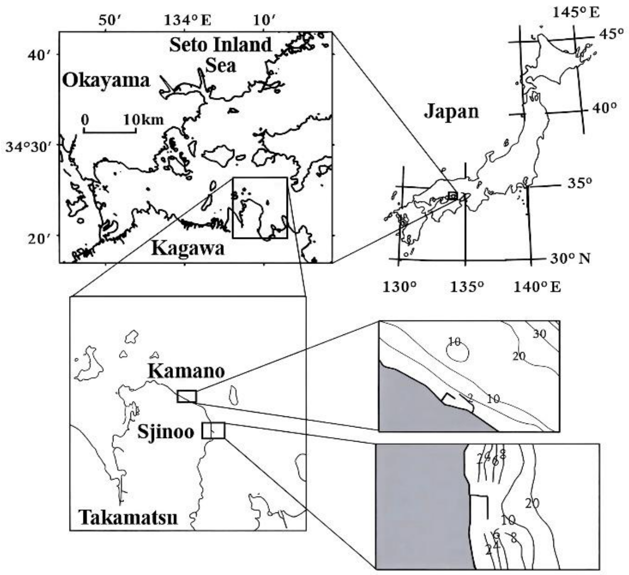

Fig. 2 Locations of the Survey Sites

A total of 72 artificial seaweed bed reefs were deployed: 25 units in the Kamano area and 47 units in the Shinoo area (Fig. 2). Numerical values indicate water depth (m), while underlined numbers denote the number of artificial seaweed bed reef units.

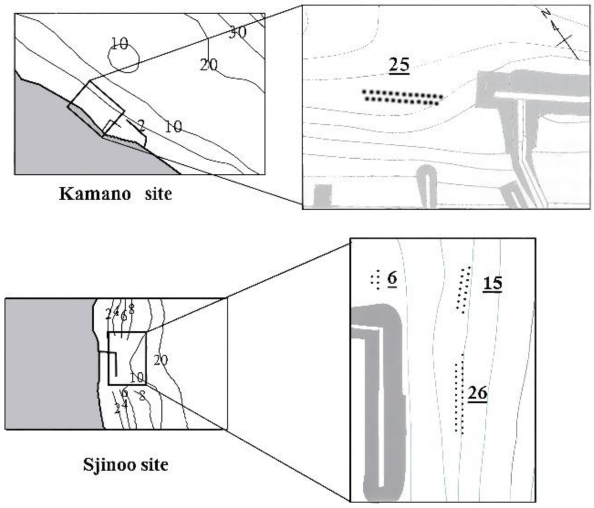

Fig. 3 Locations of the Survey Sites and Reef Deployment Details

3.2 Artificial Seaweed Bed Reefs and Porous Structures

The artificial reef structures feature a two-tiered design: the lower tier functions as a stable foundation and helps to regulate local water flow, while the upper tier, referred to as the "roof," serves as a substrate for macroalgal attachment and growth. The roof section is perforated with multiple holes to facilitate the transplantation of parent algae. It is also designed to accommodate the attachment and detachment of modular protruding components manufactured separately (Fig. 4). The structure is named “Marine Mash” due to the mushroom-like appearance of its protruding components.

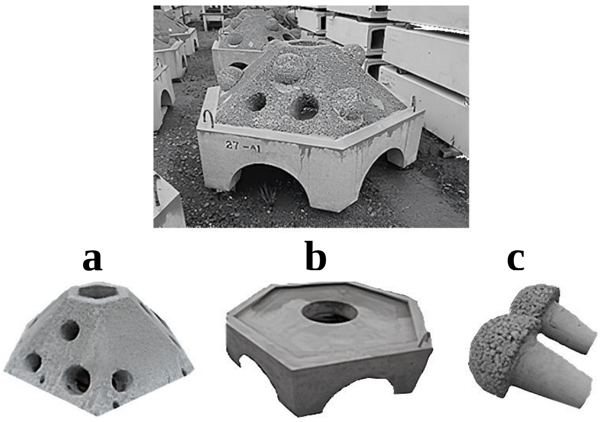

Fig. 4 Structural Components of the Artificial Seaweed Bed Reef

(a) Porous roof section
(b) Concrete foundation section
(c) Porous protruding component

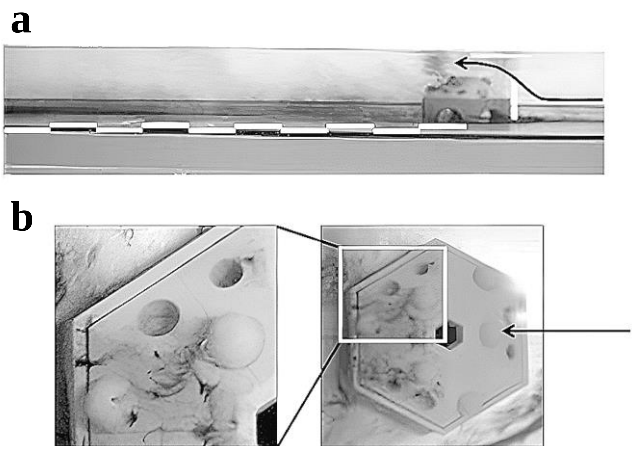

Fig. 5 Flow Conditions Surrounding the Structure
(a) Side view; (b) Top view. Arrows represent the direction of water movement.

The specific geometry of the structure influences the surrounding hydrodynamics, as illustrated in Fig. 5, which shows the flow patterns in both side and top views.

The roof and protruding components are constructed from a specialized porous material designed to foster complex biological communities. The substrate is fabricated using blast furnace slag aggregate with a graded particle size distribution of 2–20 mm (mean diameter approximately 5 mm), bound with Portland cement mortar to achieve a target void ratio of approximately 25% (Fig. 6).

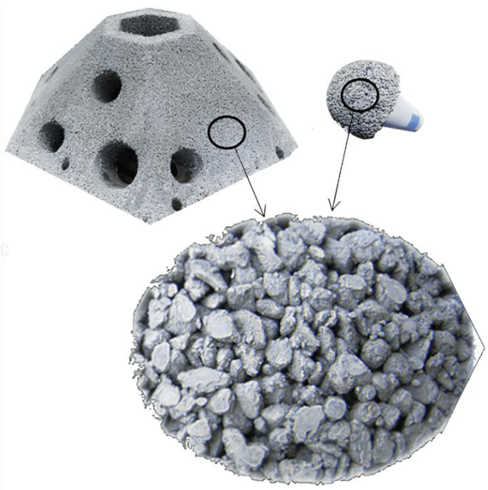

Fig. 6 Porous Substrate Structure

This graded particle size creates a hierarchical surface structure: larger particles form macroscale interstitial spaces for sessile invertebrates and algal holdfasts, while smaller particles (~2 mm) generate fine surface concavities providing optimal microhabitats for algal spore settlement. This multi-scale pore structure promotes the production of prey organisms that attract fish and other marine life [10–12], thereby serving as a potential feeding ground for higher trophic levels.

The sloped roof design (approximately 45° inclination) is a functional hydrodynamic feature for maintaining these porous surfaces. In coastal areas with low current velocities, the accumulation of fine sediment (suspended mud) on substrate surfaces physically prevents the attachment of seaweed spores and limits their survival. Therefore, incident horizontal tidal currents are designed to accelerate along the slope, generating bed shear stress that actively prevents sediment accumulation (Fig. 7).

This sediment control mechanism is a prerequisite for macroalgal recruitment, as demonstrated by comparative observations in which flat plates of the same material parallel to the seabed accumulated mud and supported almost no growth. Furthermore, as demonstrated in Fig. 5, the modular protruding components generate complex vortices that promote the settlement of spores transported by the flow.

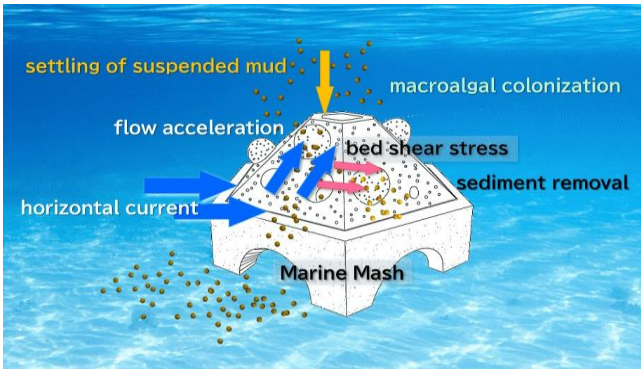

Fig. 7 Hydrodynamic Sediment Control Mechanism of the Marine Mash Structure.
Horizontal tidal currents are accelerated along the sloped roof, generating bed shear stress that removes fine sediments from the attachment surface, enabling macroalgal colonization.

3.3 Blocks for Sessile Organism Recruitment Experiments

Multiple sampling blocks (experimental units) were deployed on the roof section of artificial seaweed reef beds. These blocks measured either 18×18×6 cm or 30×30×6 cm (length × width × height) and were fixed at consistent positions throughout the study period. Sampling was conducted annually in March, corresponding to the peak growth period of the dominant macroalga *Undaria pinnatifida*, and was maintained consistently over the entire monitoring period of more than 13 years using the same field methodology and personnel.

One sampling block per substrate type was deployed and measured per annual survey (n=1 per substrate type per year); the 13-year period therefore provides n=13 temporal observations for statistical analysis. All attached organisms retained on a 1-mm mesh sieve were identified, and both the number of individuals and the biomass for each species were quantified.

Biomass of sessile organisms on rigid substrate blocks is expressed per unit volume ($kg \cdot m^{-3}$), reflecting the physically defined volume of the sampling unit. Biomass of epiphytic organisms on algal thalli is expressed per unit wet weight of algal tissue ($g \cdot kg^{-1}$), as the irregular morphology of algal thalli makes volumetric standardization impracticable; both units are consistent with standard practice in benthic and epiphyte ecology respectively.

As control units, three material types were utilized: natural stone reefs (20×20×20 cm), concrete plates (30×30×6 cm), and steel plates (30×30×2 cm). Organisms adhering to the surfaces of these control materials were measured similarly. Results were converted to values per unit volume ($g \cdot kg^{-1}$) for annual comparisons across different substrate types.

Among the collected sessile organisms, three phyla—Mollusca, Annelida, and Arthropoda—were selected as preferred prey organisms due to their potential as food sources for fish and other marine animals. Statistical analyses were performed to examine differences in their occurrence.

3.4 Assessment of Algal Growth Conditions

Algae within a defined area (50 × 50 cm) on the artificial seaweed bed reef were harvested from their attachment base, and their dry weight was measured to estimate the standing crop per unit area (m²).

Sampling was conducted in March, corresponding to the peak period of algal growth. For comparison, algal biomass was also measured on natural stone reefs located adjacent to the artificial structures.

3.5 Assessment of Epiphytic Organism Occurrence

Epiphytic organisms residing on the surface of algal thalli attached to the artificial seaweed bed reefs were collected concurrently with algal biomass sampling. Their wet weight (g) was quantified per unit wet weight (kg) of algal thalli to evaluate the relative abundance of epiphytic organisms.

4. RESULTS

4.1 Occurrence of Sessile Organisms on Porous Materials

Fig. 8 presents the annual variation in biomass ($kg \cdot m^{-3}$) of preferred prey organisms among the sessile communities that developed on porous substrates, in comparison with those on other materials such as stone, concrete, and steel.

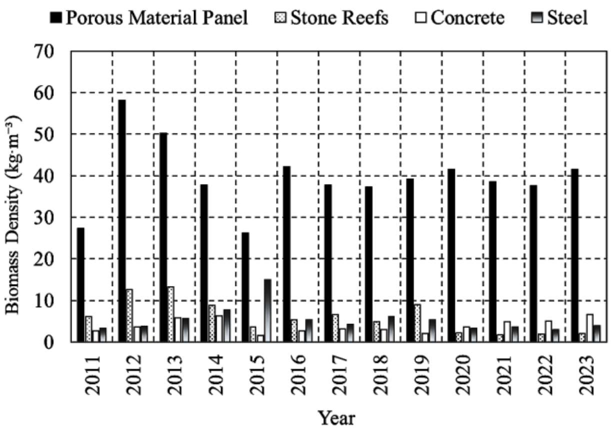

Fig. 8 Temporal Changes in Biomass of Preferred Prey Organisms on Porous Artificial Seaweed Reef Substrate

4.2 Algal Growth Conditions

Fig. 9 illustrates the biomass per unit area of algae attached to the porous substrate of the Marine Mash artificial seaweed reef (specifically, its roof and protruding components) and to other materials (natural stone).

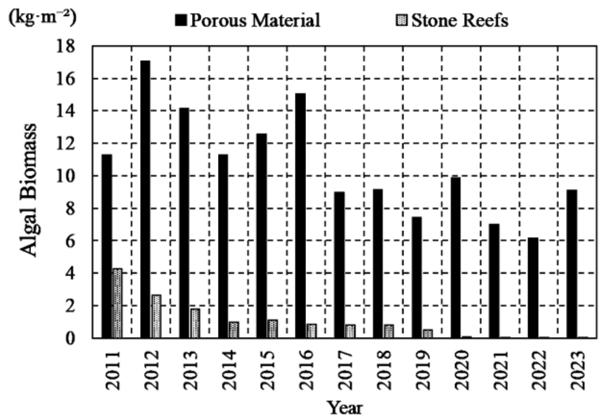

Fig. 9 Temporal Trends in Algal Biomass on Artificial Seaweed Reef Substrates

4.3 Epiphytic Fauna Development

Fig. 10 illustrates the annual variation in the biomass (g·kg^{-1}) of epiphytic organisms on attached algae.

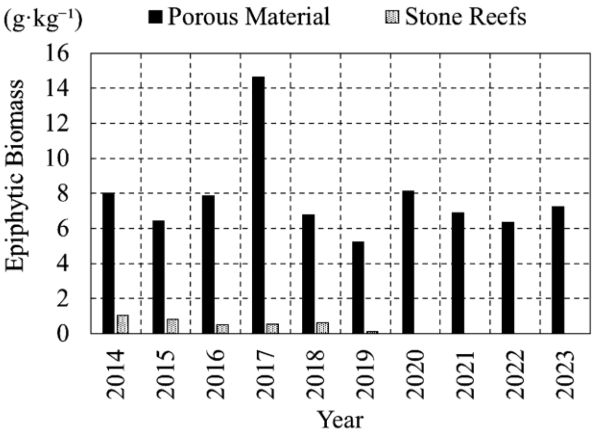

Fig. 10 Temporal Trends in Biomass of Epiphytic Organisms on Attached Algae

5. DISCUSSION

5.1 Occurrence of Preferred Prey Organisms on Porous Substrates

The porous substrate exhibited significantly higher biomass of preferred prey organisms compared to other materials. An ANOVA conducted to assess differences in the mean biomass of preferred prey organisms between the experimental group (porous substrate) and the three control groups revealed a highly significant effect (F=161, p <0.01). Post hoc tests further confirmed significant differences between the porous substrate and each of the control groups (p <0.01). These findings suggest that the porous substrate may support a substantially greater biomass of preferred prey organisms than commonly used reef materials such as natural stone, concrete, and steel.

The mechanistic basis for this enhanced prey organism production can be attributed to three interacting processes. First, hydrodynamic sediment control via the sloped roof geometry (as shown in Fig. 6) maintains clean, sediment-free surfaces that support primary colonization by macroalgae, whose presence in turn creates structured habitat for invertebrate prey.

Second, organic particle retention within the graded porous network (particle size 2–20 mm, mean 5 mm, void ratio 25%) creates a locally enriched food microenvironment: suspended organic particles—including phytoplankton, detritus, and microorganisms—tend to be retained within the interstitial spaces, potentially providing a concentrated food supply for filter feeders and deposit feeders (Mollusca, Annelida, Arthropoda) constituting the prey organism community [12, 15].

Third, the three-dimensional interstitial network reduces predation pressure on small invertebrates by physically excluding larger predators, thereby sustaining higher prey organism densities than open surfaces of non-porous materials. The observed increase in prey biomass is consistent with mechanisms reported in previous studies of artificial reef structures, including reduced near-bed flow velocity and enhanced retention of suspended organic particles within interstitial spaces.

It has been widely reported that such structural complexity enhances secondary production on artificial substrates, particularly in semi-enclosed coastal seas, and similar trends have been observed for porous artificial reef systems in previous GEOMATE studies [15,16]. The present findings quantitatively demonstrate and extend these observations by providing long-term field evidence of enhanced prey organism biomass associated with porous substrates.

5.2 Algal Growth Assessment

A paired t-test comparing algal biomass between the experimental reef structure "Marine Mash" and the control reef (stone-based) revealed a statistically significant difference (t (12) = 12.475, p < 0.01). The exceptionally small p-value ($p = 3.16 \times 10^{-8}$) indicates that this observed difference was highly unlikely to have occurred by chance. These findings suggest that the porous substrate incorporated into the Marine Mash reef structure may promote algal growth.

5.3 Epiphytic Fauna on Algal Surfaces

A paired t-test comparing the biomass of epiphytic organisms on algae between the experimental reef structure 'Marine Mash' and the control reef (stone-based) revealed a statistically significant difference (t (9) = 9.3, p < 0.01), and the exceptionally small p-value ($p = 6.51 \times 10^{-6}$) indicates this difference was highly unlikely to have occurred by chance. These findings suggest that the porous substrate incorporated into the Marine Mash reef structure may promote the development of epiphytic fauna on algal surfaces.

Although elevated epiphytic biomass could theoretically reflect reduced grazing pressure rather than enhanced production, this interpretation is unlikely to explain the observed difference: both the Marine Mash and stone control substrates were deployed at the same sites and were therefore exposed to the same grazing community, including fully mobile herbivorous fish that access both substrate types equally.

Furthermore, horizontal control plates of the same porous material accumulated sediment and supported almost no macroalgal growth under the same grazing conditions, demonstrating that grazing exclusion alone cannot account for the observed differences. The dominant macroalga *Undaria pinnatifida* developed dense canopies of approximately 1 m height during peak growing season, which is more consistent with sustained high productivity than suppressed grazing.

We therefore interpret the significantly higher epiphytic biomass on Marine Mash algae as primarily reflecting enhanced epiphytic production associated with the enriched food microenvironment of the porous substrate, while acknowledging that the contribution of differential grazing effects cannot be entirely excluded.

5.4 Integrated Ecological Functionality of the Marine Mash Structure

The results presented in Sections 5.1–5.3 collectively demonstrate that the Marine Mash structure provides multiple, interrelated ecological functions within the restored seaweed bed. The porous substrate enhanced the availability of preferred prey organisms, promoted macroalgal growth, and increased the biomass of epiphytic fauna, indicating a positive cascading effect across multiple trophic levels.

Such integrated functionality suggests that the effectiveness of the Marine Mash structure cannot be adequately evaluated using a single indicator. Instead, its ecological value lies in the synergistic enhancement of habitat provision, food resource availability, and primary production. These functions are considered important for sustaining fishery resources and maintaining ecosystem resilience, particularly in semi-enclosed coastal seas where environmental carrying capacity is constrained.

From a broader perspective, the Marine Mash structure represents a hybrid approach that combines engineered design with ecological principles, aligning closely with the concept of Nature-based Solutions. By facilitating self-sustaining biological processes without continuous external inputs, this approach offers a practical and scalable option for long-term coastal ecosystem restoration under conditions of nutrient management and climate change.

Similar conclusions have been suggested in recent studies on artificial reef evaluation, which emphasize the importance of assessing structures based on multiple ecosystem services rather than single performance indicators alone [11,12].

6. CONCLUSIONS

This study evaluated the ecological functionality of seaweed bed creation structures utilizing porous materials (Marine Mash) based on long-term field observations conducted in the Seto Inland Sea, Japan. By focusing on ecosystem functions rather than attachment success alone, this research provides a comprehensive assessment of structure-based seaweed bed restoration under oligotrophic coastal conditions.

The results demonstrate three key findings. First, porous substrates supported significantly higher biomass of preferred prey organisms compared with conventional materials, indicating enhanced food resource availability for higher trophic levels. Second, the Marine Mash structure promoted substantially greater macroalgal biomass than stone-based control reefs, suggesting that substrate design plays a critical role in sustaining primary production even under nutrient-limited conditions. Third, the biomass of epiphytic organisms on algal surfaces was significantly increased on the porous structures, highlighting the cascading enhancement of associated biological communities.

Taken together, these findings indicate that the Marine Mash structure provides integrated and synergistic ecological functions, including habitat provision, food-web support, and primary production enhancement. Unlike conventional artificial reefs that are often evaluated using single performance indicators, the present study demonstrates the importance of multifunctional assessment for seaweed bed restoration technologies.

In summary, this study provides long-term field observations suggesting that porous artificial reef structures (Marine Mash) may function as hotspots of trophic productivity in oligotrophic coastal waters by integrating three complementary mechanisms: hydrodynamic sediment control via sloped roof geometry, organic particle retention and microhabitat enrichment within the graded porous interstitial network (particle size 2–20 mm, mean 5 mm, void ratio 25%), and strategic deployment on sandy mud substrate to minimize sea urchin grazing pressure.

These findings suggest that habitat structure, rather than nutrient enrichment, may drive trophic productivity in oligotrophic coastal ecosystems—a principle with broad implications for coastal restoration in semi-enclosed seas worldwide where nutrient management policies have unintentionally suppressed primary productivity.

Future research priorities include direct measurement of near-substrate hydrodynamics and sediment dynamics, systematic investigation of the relative contributions of each mechanistic component, material optimization studies varying void ratio and aggregate grading, and ecosystem-level modelling of food-web and carbon sequestration contributions.

The transferability of the Marine Mash design principle to other oligotrophic coastal regions—including the Mediterranean, the Red Sea, and other semi-enclosed seas facing similar pressures of habitat degradation and climate change—represents a particularly promising avenue for international collaboration and policy development.

From an applied perspective, the Marine Mash approach aligns closely with the concept of Nature-based Solutions by enabling self-sustaining ecosystem formation without continuous external inputs such as nutrient enrichment or repeated transplantation. The long-term stability and functionality observed in this study suggest that porous seaweed bed creation structures offer a practical and transferable option for coastal ecosystem restoration in semi-enclosed and nutrient-limited seas worldwide.

7. Future Challenges and Potential Applications

This study demonstrated that seaweed bed restoration reefs incorporating porous substrates significantly enhance the presence of preferred prey organisms, macroalgae, and epiphytic organisms. Moving forward, the following challenges and potential applications should be addressed to advance the development of this restoration approach.

First, it is necessary to verify the long-term effectiveness of the porous substrate through extended monitoring. This study's evaluations were conducted over a limited period, and the effects of biological community succession and physical degradation over time remain unclear. Additionally, to clarify the influence of seasonal variations and regional differences on the bio-attraction effect, it is essential to assess reproducibility under diverse environmental conditions.

Another challenge lies in advancing functional evaluation. For instance, assessing the extent to which biotic communities induced by porous substrates contribute to the restoration of fishery resources and carbon sequestration requires system-level analysis using ecosystem models that incorporate energy flow and material cycling.

In terms of potential applications, integrating this approach with coastal ecosystem restoration and blue carbon policies is of particular importance. Notably, this aligns well with international targets like United Nations Sustainable Development Goals (SDGs) 14 'Life Below Water' and 13 'Climate Action' [17], and holds promise for implementation as a nature-based solution [16,18].

The Intergovernmental Panel on Climate Change (IPCC) recognizes seagrass meadows and mangroves as established blue carbon ecosystems, and acknowledges that seaweed beds may also contribute to coastal carbon cycling as part of Nature-based Solutions (NbS) [2,19]. This study's quantification of seaweed bed biomass provides foundational data for evaluating their potential role in coastal ecosystem restoration and climate change mitigation strategies.

The fabrication of artificial reef materials from regional resources, including industrial by-products, demonstrates high compatibility with the local production for local consumption paradigm. Furthermore, the integration of fishery waste into porous concrete bases represents a promising direction for achieving carbon neutrality while managing marine resources [20].

This synergistic approach is anticipated to both lessen environmental burdens and engender favorable regional economic multipliers. Future efforts must encompass a thorough assessment of the scientific and societal importance of these initiatives, alongside the systematic accumulation of knowledge pertinent to domestic and international policy development and environmental assessments. Additionally, actively investigating opportunities for engagement within international frameworks is a key consideration.

8. ACKNOWLEDGMENTS

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