Limlunjakorn *Discover Sustainability* (2025) 6:783
https://doi.org/10.1007/s43621-025-01691-y

Discover Sustainability

RESEARCH Open Access

The designing of 3D-printed modular artificial reefs through design thinking framework: a case study in Koh Khai, Chumphon Province, Thailand

Torpong Limlunjakorn[1]*

*Correspondence:
Torpong Limlunjakorn
Torpong.li@kmitl.ac.th;
Limlunjakorn@hotmail.com
[1] Faculty of Architecture, Art, and Design, King Mongkut's Institute of Technology, Ladkrabang, Bangkok, Thailand

Abstract
Coral reefs degradation in Thailand demands scalable, community-accessible restoration solutions. This study addresses the limitations of conventional artificial reefs by developing 3D-printed modular artificial reefs (3DMARs) optimized for ecological performance, usability, and low-resource deployment. Formulated through the lens of design expertise and applying a design thinking framework, the research integrates qualitative content analysis, interdisciplinary collaboration, and user-centered design to establish key criteria, including modularity, flexibility, and environmental sustainability. Prototypes were co-developed with SCG Co., Ltd. Field deployment at Koh Khai, Chumphon Province, demonstrated ease of transport, manual installation, and ecological compatibility. Initial observations suggest that the system enhances coral habitat complexity while promoting local engagement. The study presents a replicable and adaptable model for decentralized reef restoration, supporting sustainable marine efforts in regions with limited technical capacity, such as Thailand and similar Southeast Asian coastal areas.

Keywords Artificial coral reefs, 3D printing, Modularity, Design thinking

1 Introduction

Artificial reefs (ARs) have been increasingly utilized worldwide to rehabilitate degraded marine habitats, enhance biodiversity, and support the livelihoods of coastal communities [1–3]. As anthropogenic pressures and climate-induced stressors, such as coral bleaching, overfishing, and habitat degradation, escalate, a broad range of materials and design approaches have been employed globally, from purpose-built reef units to repurposed industrial components, reflecting the diversity of environmental conditions, economic capacities, and technological capabilities across regions [4–6]. ARs commonly represent a convergence of ecological engineering and structural design, functioning as three-dimensional substrates that replicate the complexity of natural coral reefs systems [7, 8]. When strategically deployed, they contribute to the restoration and protection of marine ecosystems by enhancing fish biomass and biodiversity while providing essential habitat, shelter, and breeding grounds for various aquatic species [9–12]. Recent global case studies further demonstrate the evolving scope of ARs applications. For example, reef systems and eco-engineered structures have been deployed in regions that are tailored to local ecological needs and community involvement. Dubai Reef Project, UAE, with 20,000 purpose-built reef modules, which replenish fish stocks and boost coastal biodiversity, as well as enhance carbon sequestration [13]. MARRS reefs rehabilitation project, hundreds of hexagonal steel structures, at the Great Barrier Reef, Australia, indicated that coral cover rose from 15 to 25%, fish diversity per transect increased from 24 to 32 species, < 2% mortality of coral fragment attachment [14, 15] Artificial reefs project in Pulau Weh, Aceh, Indonesia, which 260 concrete modules, showed abundant coral recruits and fish life; comparative surveys vs. natural reefs showed competitive performance in coral cover and biodiversity [16]. Algeria's first artificial reef project along the Oran coast, which utilized 68 module units to increase local marine biodiversity by a factor of 9.25 [17].

Thailand, where coral reef ecosystems are experiencing severe decline. Reports indicate thatffig up to 30% of shallow-water corals in the region have been affected by bleaching, with 5–15% experiencing severe damage [18]. It has also initiated various marine conservation programs through artificial reefs projects [19]. Since the 1980s, institutions such as the Southeast Asian Fisheries Development Center (SEAFDEC) have implemented ARs across the Andaman Sea and the Gulf of Thailand [20–21], utilizing concrete blocks, decommissioned vehicles, and offshore platform components to provide habitat and support local economies [22–25]. In recent years, updated efforts have emphasized ecological design and public engagement. For instance, pilot programs involving eco-friendly materials and community-based deployment have been introduced in provinces such as SEACOSYSTEM from several sectors for the conservation of Thailand's sea and partners, which is deploy more than 1,000 cubic concretes of artificial reefs modules in Songkhla and Narathiwat province to conserve sea resources and restore sustainable coastal fishery [26]. As well as the placement of approximately 3,000 concrete cubic frames by a marine restoration project led by the Department of Marine and Coastal Resources of Thailand [27]. The concrete cubic frames have been a commonly used artificial reefs structure in Thailand, and were deployed at irregular intervals from 2013 to the present, either a single tier or a stack of two tiers at depths ranging from 8.5 to 20 m [28]. Moreover, incorporating advanced 3D printing technologies into artificial reefs design has enabled the development of modular, environmentally sustainable structures that incorporate high-resolution biomimetic forms and site-specific adaptability [29]. As demonstrated by the Coral Reef Restoration Project by the Earth Agenda Foundation and private partners, which deployed 109 structures at Koh Racha Yai, Phuket, these structures mimic natural coral forms to support coral growth [30]. Although traditional coral restoration techniques such as transplantation have demonstrated moderate success in promoting coral regrowth [31], many ARs initiatives remain dependent on large, monolithic structures that are logistically demanding and resource-intensive (Fig. 1). These conventional installations often require specialized expertise, heavy equipment, and transport infrastructure, which limits their applicability in remote or under-resourced, small conservation groups, regions, and undermines opportunities for broader implementation and community-led participation [32].

Fig. 1 The conventional artificial reefs installations in Thailand (Left; https://www.cpgroupglobal.com/en/newsroom/news/132/cp-group-launches-seacosystem-for-the-sustainable-thai-sea-integrating-support-from-all-sectors-for-the-conservation-of-thailand-s-sea-and-partners-with-the-department-of-fisheries-to-plant-1000-artificial-reefs, Center; https://esguniverse.com/content/251700/, Right; https://www.dailynews.co.th/news/4158947/)

To address these limitations, emerging design strategies are exploring the use of modular artificial reef systems. By incorporating modularity, ARs units can be fabricated in smaller, transportable components that are easy to deploy and configure based on site-specific requirements. Modular designs also allow for phased expansion and greater adaptability to varied ecological contexts [33]. This approach not only reduces logistical burdens but also facilitates community involvement in planning, deployment, and monitoring processes. Furthermore, modular connectivity enhances spatial flexibility, enabling ARs to be arranged in formations that optimize ecological function and site integration [34]. By combining digital fabrication with environmental design principles, recent advancements have led to the emergence of 3D-printed modular artificial reefs (3DMARs), which are engineered as scalable, interlocking units that support coral recruitment, enhance marine biodiversity, and facilitate efficient deployment and maintenance [35–36], introduced promising alternatives through modular construction, eco-friendly materials, and the ability to mimic natural coral forms with high customization [29, 37] The modular approach offers distinct advantages in transportability, construction flexibility, and operational efficiency, particularly in settings with limited infrastructure. Case studies such as the Yfalos Reef in Greece by Topotheque, Reef Design Lab's projects in Australia, and RRREEFS in the Philippines exemplify how modular reef systems can deliver both ecological benefits and practical scalability through material innovation and adaptive engineering [38–40]. Notably, these systems differ from traditional artificial reefs in that they can be easily transported, deployed, and installed without the need for heavy machinery, industrial vessels, or extensive logistical support. Their modularity also allows for expansion and customization, highlighting their potential for broader application across diverse marine environments.

Based on the academic literature review synthesized in the introduction, the design criteria for 3DMARs integrate core principles of artificial reefs effectiveness with specific adaptations suited to the Thai marine context and local deployment capabilities. Key functional attributes include the incorporation of tunnels, cavities, and voids that provide refuge and nesting spaces tailored to the body sizes of native reef fish and benthic organisms supporting both their survival and reproductive success [41–45]. Surface texture is another essential consideration; roughened exteriors promote the settlement of coral larvae and other sessile organisms, enhancing reefs establishment and biological colonization [46–48]. Furthermore, the use of durable yet straightforward forms is prioritized to maximize ecological function while maintaining ease of production and deployment. These configurations align with coral nursery practices, where fragment-based and tuber-shaped modules have shown increased effectiveness in facilitating coral rehabilitation [31, 49–50]. Emphasizing modularity allows individual units to be fabricated, transported, and assembled independently, encouraging flexible arrangement, reduced cost, and user accessibility, especially for communities with limited technical resources [51–53]. Incorporating 3D printing with sustainable, cement-based materials further enhances the ability of artificial reefs. modules to mimic natural coral morphologies, allowing them to adapt to local seabed conditions and environmental parameters. As a result, these structures hold significant potential for improving ecosystem restoration outcomes while contributing to broader marine conservation goals [54–55]. A summary of these global design strategies is illustrated in Table 1.

Although interest in adaptable artificial reef systems is growing in Thailand, there remains limited research focused explicitly on modular 3D-printed reefs that combine interconnectivity in both vertical and horizontal configurations while maintaining a compact size suitable for handling by a single individual. Existing initiatives, such as Chulalongkorn University's Innovareef and the Earth Agenda Foundation project developed in collaboration with SCG Co., ltd, emphasize nature-inspired, separable units [56, 57]. However, these initiatives do not address modular systems optimized for logistically efficient, community-driven deployment by user-centric design principles. Addressing this gap, the present study applies a Design Thinking framework to develop standardized, small-scale modular reef units designed for affordable mass production and local deployment without reliance on specialized equipment [53, 58]. This approach directly responds to Thailand's transportation and resource limitations, contrasting with global 3DMARs projects that rely on high-tech fabrication processes and intricate assembly systems.

To achieve this objective, the research centers around the following question: How can a modular, small-scale 3D-printed artificial reef systems be designed with specific design criteria for community-driven deployment in Thailand? The study hypothesizes that: A modular, small-scale 3D-printed artificial reef systems, designed using a user-centric approach, will effectively balance operational efficiency with ecological effectiveness, considering the local constraints of Thailand. To test this hypothesis, a pilot deployment is planned from October 2023 to October 2024 off the coast of Koh Khai in Chumphon

Table 1 Table showing the general design criteria for 3DMARs, as synthesized from the global literature review

Design Criterion	Description	Purpose/function	Supporting references
Modularity	Small, interlocking units for phased expansion and flexible arrangements	Transportability, ease of deployment, and adaptability	[29, 33–40, 51–53]
Internal voids, tunnels, cavities	Structures with varying cavity sizes, tunnels, and open spaces	Refuge, nesting for reef fish and benthic organisms	[41–45]
Surface texture	Roughened or grooved surfaces	Promotes coral larval settlement and biological colonization	[46–48]
Form simplicity and durability	Simple, robust forms that balance ecological function with production efficiency	Facilitates mass production, community deployment	[31, 49, 50]
Material sustainability	Use of eco-friendly cement composites, ceramics, or resins	Environmental compatibility, durability	[29, 37, 54, 55]
Customizable morphology	Ability to mimic natural coral shapes through 3D printing	Enhances habitat complexity, site-specific adaptation	[29, 35–37, 54, 55]
Community accessibility	Designed for easy handling, transport, and installation by local communities	Reduces cost and reliance on heavy machinery	[29, 33–40, 51–53]

Province, followed by six months of ecological monitoring to evaluate both ecological adaptability and community engagement outcomes.

Koh Khai (10.55° N, 99.10° E), a nearshore island in Chumphon Province, along the Central Gulf of Thailand, was selected for the installation site due to its suitable environmental and logistical conditions. The site, located on the island's southwest side, approximately 3 km from Ban Hin Kob pair (local coastal community), features a 25-square-meter sandy and rubble-strewn seabed at an intermediate depth of 6–12 m. Environmental assessments indicated stable salinity (33–35 PSU), temperatures of 28–30 °C, low turbidity, and moderate current velocity conditions favorable for coral recruitment and reefs development [59–60]. Seasonal upwelling further supports biodiversity through the cycling of nutrients. The site hosts reef-associated species such as Acropora and Porites and aligns with ongoing marine rehabilitation by Thailand's Department of Marine and Coastal Resources (DMCR). Deployment was carried out in collaboration with local divers using small boats and manual methods, demonstrating the design's adaptability to low-resource, community-led implementation. The map showing the installation site at Koh Khai is indicated in Fig. 2.

The study acknowledges certain limitations due to budgetary constraints, which hinder the number of 3DMARs units that can be produced and the extent of post-deployment ecological monitoring. Its primary focus is on the design development, deployment methodology, and initial real-world implementation of modular artificial reefs. In-depth investigations into coral larvae colonization, biodiversity enhancement, and long-term ecological dynamics fall outside its immediate scope. Advancing these fields will necessitate ongoing interdisciplinary collaboration, particularly with marine biologists, to further build on this foundational framework.

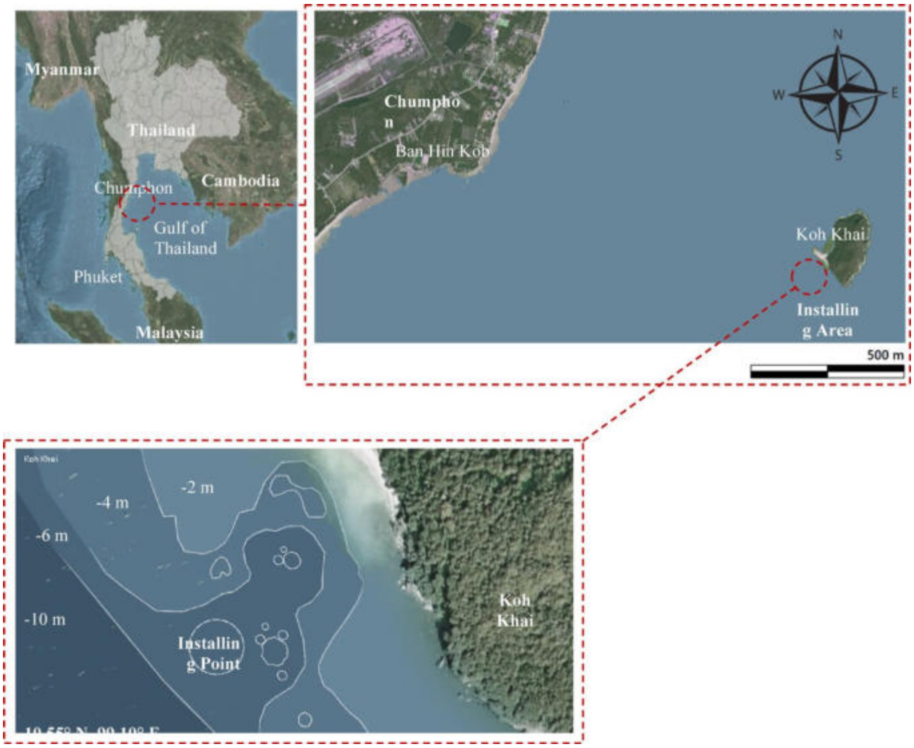

Fig. 2 Map showing the location of the 3D-printed modular artificial reefs (3DMARs) installation site at Koh Khai, Chumphon Province, Thailand. Illustration by Torpong Limlunjakorn

2 Methodology

2.1 Applying the design thinking framework

This research, formulated through the lens of design expertise, utilizes the Design Thinking framework, structured into six iterative phases: empathize, define, ideate, prototype, test, and implement [61]. This human-centered methodology is applied to guide the development of 3DMARs, addressing complex, real-world challenges through interdisciplinary problem-solving. By integrating scientific, ecological, and technological inputs, the framework supports sustainable reef development. Its adaptability facilitates the transformation of conceptual ideas into scalable, site-specific solutions. Furthermore, the application of design thinking enhances innovation, stakeholder engagement, and environmental responsiveness, resulting in prototypes that are both ecologically viable and technically robust [62–63]. The research process is summarized in Table 2, which outlines the key steps involved.

(a) *Empathize stage*: Gain deep insights into the context; this stage focuses on gathering information through literature reviews, surveys, and interviews to understand the actual problems, emphasize the needs of the user, and comprehend the physical context. The details of this stage are as follows:

- Literature Review: Analyzes documents and research to obtain preliminary data on artificial reefs design standards and theory, including the advantages/disadvantages and other limitations.
- Field Study Surveying: Collects data from specific locations to comprehensively understand the context, overall situation, and other limitations.
- Experts Interview: Interviews with experts focus on understanding the needs, user-centric perspective, practical implementation, related problems, and other relevant factors.

(b) *Define stage*: This stage focuses on analyzing data collected during the Empathize stage, identifying constraints and key factors through qualitative content analysis.

Table 2 Table of research procedure, through the design thinking approach

Phase	Objective	Key activities	Output
Empathize	Understand ecological and user needs.	Literature review, field surveys (Koh Larn, Koh Racha, Koh Khai), expert interviews	Contextual insights and user requirements
Define	Identify key challenges and design criteria	Data analysis, synthesis of findings	Problem statement and thematic design criteria
Ideation	Generate and develop design concepts.	Establish Design Criteria, CAD modeling, modular form exploration, feasibility analysis, and the design process.	Preliminary, Schematic, and Final design of 3DMARs
Prototyping	Build and refine physical prototypes	3DMARs prototyped, material testing	Full-scale prototypes for evaluation
Testing	Assess design performance and usability	Controlled environment testing, modularity, and handling assessment	Validated performance and refinement data
Implementation	Real-world deployment and stakeholder engagement	Deployment at Koh Khai involves community collaboration, 3D documentation of the deployment process, and interviews with stakeholders to gather feedback on the post-deployment outcomes.	Installed the reef system and post-deployment feedback

This analysis emphasizes user-centric and environmental considerations to establish a clear problem statement and actionable design criteria for 3DMARs.

(c) *Ideation stage*: This phase involves close collaboration with SCG Co., Ltd. to develop prototypes. The prototypes are manufactured at SCG's facilities, utilizing various experimental materials and 3D printing techniques to evaluate the strengths, limitations, and practical feasibility of each design. This approach offers an opportunity to evaluate the prototypes in a real-world setting, which is structured into three distinct phases—preliminary design, schematic design, and final design, reflecting standard stages within the professional design development framework. The resulting refined prototypes are designed to effectively balance user-centric principles, environmental compatibility, and stakeholder requirements.

(d) *Prototyping stage*: This phase involves close collaboration with SCG Co., Ltd. to develop prototypes. The prototypes are manufactured at SCG's facilities, utilizing various experimental materials and 3D printing techniques to evaluate each design's strengths, limitations, and practical feasibility. This approach provides an opportunity to assess the prototypes in a real-world context, which are designed to balance user-centric principles, environmental compatibility, and stakeholder requirements effectively.

(e) *Testing stage*: During the testing phase, the prototypes are evaluated in a controlled pool environment to simulate real-world underwater conditions and assess their effectiveness. Critical parameters, including usability, weight, buoyancy control, transportation logistics, underwater handling, and modular configuration, are systematically analyzed. This phase serves to validate the design criteria, ensuring the readiness and suitability of 3DMARs for practical implementation in real-world settings.

(f) *Implementation stage*: The implementation phase entails deploying 3DMARs in a real-world setting, encompassing logistics, transportation, and installation at Koh Khai, Chumphon. This process involves close coordination with the local coastal community to address equipment constraints and ensure the practical usability of the equipment. Data collection methodologies include 3D reconstruction techniques and stakeholder feedback to assess the project's effectiveness comprehensively. The approach prioritizes human-centered design, collaboration, and sustainability, fostering long-term benefits and active community engagement.

2.2 Empathize phase

2.2.1 Field study surveying

To understand the current condition of artificial reefs installations in Thailand, a field study was conducted across three geographically and ecologically distinct sites between April and July 2024. The selected locations situated in the Central Gulf of Thailand (Koh Larn), the Lower Gulf of Thailand (Koh Khai), and the Andaman Sea (Koh Racha) were chosen to reflect a diverse range of environmental conditions, coral species, and levels of human intervention. Site selection criteria included geographic distribution, ecological variation, depth profiles, and the presence or absence of artificial reef initiatives. Although the surveyed sites differ in depth, approximately 4–6 m at Koh Larn, 6–12 m at Koh Khai, and 10–14 m at Koh Racha, these variations fall within the typical depth range suitable for coral growth and artificial reefs placement. Therefore, the depth differences are not expected to result in significant deviations in the study outcomes. This approach facilitated a comparative evaluation of material strategies, structural typologies, and community participation across tourism-driven and restoration-focused reef contexts. It also examined context-specific design responses and assessed the ecological and social impacts of artificial reef implementation, as detailed below.

Koh Larn (Larn Island), located in Chonburi Province in the upper Gulf of Thailand, features a seabed characterized by small hard corals, such as lettuce corals, on a flat substrate with an average depth of 4–6 m. The site includes artificial reefs designed for coral restoration and tourism activities, including sea walking and snorkeling. These artificial reefs, constructed from resin materials, are designed to support the propagation and attachment of live coral species, such as staghorn coral, thereby enhancing marine habitats and blending harmoniously with the underwater environment, also promoting tourism. The structures are approximately 1.00–1.20 m in height, optimized for human observation at eye level. Additionally, the area features railings and clearly defined flooring zones to enhance visitor safety and accessibility.

Koh Racha (Racha, Island), located in Phuket Province, in the Andaman Sea, features a diverse underwater environment with medium-to-large species of hard corals distributed across the flat and sloping seabed, with an average depth of 10–14 m, accompanied by excellent water visibility. Several artificial reef projects have been implemented at this site to enhance marine ecology and promote tourism, particularly scuba diving. The artificial reefs vary in size and form, including free-form designs, cubic geometries, and domes with voids strategically incorporated to mitigate underwater wave impacts. Some structures mimic natural forms, allowing for seamless integration with the marine environment. Initiated in 2017, these projects have yielded promising results, including enhanced coral larval attachment to reef surfaces and the establishment of marine habitats.

Koh Khai (Khai Island), located in Chumphon Province, in the central gulf of Thailand, features a marine environment dominated by soft corals and medium-sized hard coral species, notably barrel sponges and lettuce corals. The site has moderate water visibility and an average depth of 6 to 12 m. During the monsoon season, typically from September to January, coastal areas in Thailand often experience strong and turbulent water currents. Unlike the previous sites, Koh Khai does not host any established artificial reef projects. However, it is designated as a priority area for marine ecosystem restoration due to its shallow coral reefs, high marine biodiversity, and suitability for coral nursery activities. Local knowledge plays a pivotal role in restoration efforts, with community members utilizing generic PVC structures connected by tubes to create small-scale frameworks. These frameworks are used to attach live coral branches, such as staghorn coral fragments, facilitating coral rehabilitation. However, based on the site survey conducted at Koh Khai, the designated pilot location for this project, several logistical constraints were identified, particularly regarding the availability of equipment. The coastal community of Ban Hin Kob, which serves as the operational base, primarily relies on small, locally modified fishing boats for marine activities (Fig. 3). These vessels are not equipped with specialized tools, such as cranes, that could facilitate the deployment of artificial reef modules. Furthermore, the shallow reef zones surrounding Koh Khai present additional challenges, as they restrict access for larger vessels, making standard deployment methods impractical in this context.

Fig. 3 The context of Ban Hin Kob, local coastal community (left to right), Image courtesy of Torpong Limlunjakorn

Fig. 4 Rasin Artificial reefs for coral restoration and tourism in Koh Larn (top left, top center), Several artificial reefs for coral restoration and for tourism in Koh Racha (top right, below left), coral rehabilitation program in Koh Khai, using staghorn coral fragments attached to PVC framework (below center, below right), Image courtesy of Torpong Limlunjakorn

The observations and insights gathered from the survey sites are essential for understanding the underwater environment and its limitations. This information serves as a foundation for designing and implementing artificial reef projects in Thailand. The survey data will be systematically organized into thematic categories for further analysis. Additionally, the findings highlight the advantages and potential applications of using site-specific approaches to reef development. A detailed representation of the entire underwater survey process can be seen in Fig. 4.

2.3 Expert interviewing

2.3.1 Selecting criteria

To gather diverse, practice-based insights into the design and deployment of 3DMARs, semi-structured interviews were conducted from March to May 2024. The participants were selected from three stakeholder groups: 3D printing experts, coastal conservation specialists, and local community members with coastal interests. Participants were chosen based on their relevant professional qualifications, institutional affiliations, and demonstrated expertise. The 3D printing experts were sourced from a nationally recognized additive manufacturing laboratory, each possessing over five years of experience in biomimetic marine applications. Coastal conservation specialists were affiliated with the Department of Marine and Coastal Resources (DMCR) or leading marine science organizations. Community members had a long-term involvement (a minimum of ten years) in small-scale fisheries, coral conservation, or local resource management. All participants voluntarily consented to the interviews, which were conducted by strict ethical protocols regarding confidentiality and data protection.

2.3.2 Interview procedure

To inform the development of the 3DMARs, a series of semi-structured interviews was conducted with three key stakeholder groups: 3D printing experts, coastal conservation professionals, and members of the local coastal community. A total of 15 participants were interviewed; each session lasted approximately 15 to 20 min and was conducted at context-appropriate locations, including additive manufacturing laboratories, coral restoration sites, and community gathering spaces. Interviews were recorded in both audio and paper formats, supplemented by detailed notetaking, followed by an interview guide structured around reef design, technical feasibility, ecological function, and practical usability (see the interview guide in[1]). Transcripts were analyzed using thematic content analysis, enabling the triangulation of perspectives from technical, ecological, and user-centered domains. This process ensured that stakeholder insights were meaningfully integrated into each design phase, reinforcing the project's interdisciplinary foundation.

Discussions with 3D printing experts ($n = 5$) centered on additive manufacturing technologies, constraints of underwater deployment, and the potential of sustainable, eco-friendly materials to enhance coral larvae rate and reduce carbon emission in the manufacturing process. Their technical input was particularly valuable in refining modular configurations for printing feasibility, stacking mechanisms, and surface textures conducive to coral settlement, as well as this layered 3D printing limitation, which was reflected in the design. Interviews with coastal conservation professionals ($n = 5$), many of whom were engaged during concurrent reefs survey operations, emphasized ecological considerations such as coral larval dispersal, reef fish behavior, and the compatibility of artificial substrates with local benthic ecosystems. Finally, interviews with local coastal community members ($n = 5$), including local fishers and volunteer divers, offered critical insights into environmental conditions, traditional knowledge of underwater logistics limitations, and the practical constraints associated with installation without specialized vessels or equipment, as well as the most suitable locations for deploying artificial reefs around Koh Khai. The whole interview process is shown in Fig. 5. The data obtained from all interviews will be synthesized and utilized in the subsequent data analysis phase.

---

[1] https://docs.google.com/document/d/1KIhHdrUScoLpUZ5anrZphuy18DLvvHYS/edit?usp=drive_link&ouid=109814232294941187358&rtpof=true&sd=true.

Fig. 5 Interview with 3D-printed artificial coral production experts (left), Interview with coastal conservation experts (left center), the Example of coral larvae attached on artificial reefs surface (right center), Interview with local community expert (right), Image courtesy of Torpong Limlunjakorn

2.4 Define phase

2.4.1 Data analysis

This study employs content analysis, a systematic qualitative research method, to derive valid and replicable inferences from data within its context. The primary objective is to generate knowledge, gain new insights, and provide a practical guide for action [64–65]. Content analysis is particularly beneficial when working with complex and multi-sourced data due to its flexibility, integration capacity, and applicability across various contexts [66]. To develop the design criteria for 3DMARs, data were collected from three key sources: (1) a comprehensive literature review, (2) site surveys, and (3) in-depth interviews with stakeholders. Each method provided distinct yet complementary insights essential to establishing context-sensitive and user-centric reefs design principles.

First, the literature review synthesized foundational theories and empirical findings related to artificial reefs design, encompassing ecological functions, structural typologies, and socio-economic impacts. A coding process was applied to extract recurrent factors, which were grouped into thematic categories, forming the analytical foundation. Second, site surveys were conducted at three representative coastal sites in Thailand, strategically selected based on geographic and ecological diversity, including the Central Gulf of Thailand, the Lower Gulf of Thailand, and the Andaman Sea. Observations included seabed characteristics, reef typologies, marine biodiversity, water depth, and human interaction. This data contributed to understanding site-specific requirements and environmental constraints in reef design. Third, fifteen semi-structured interviews were conducted with three stakeholder groups: (3.1) five experts in artificial reefs fabrication using 3D printing technology, (3.2) five coastal conservation professionals, and (3.3) five representatives from local communities involved in coral restoration. These interviews yielded valuable insights regarding practical challenges, technical feasibility, material considerations, and locally adapted practices.

The data from all three sources were systematically coded and integrated using thematic analysis. Factors were grouped by recurring design themes such as material compatibility, spatial structure, ecological performance, and stakeholder usability and cross-referenced across methods to identify overlapping and divergent patterns. Due to the manageable dataset size, coding was conducted manually and supplemented with spreadsheet tools to maintain precision and transparency. The final themes and subcategories were synthesized into a cohesive framework for 3DMAR design, which focuses on user-centric and problem-solving approaches, emphasizing feasibility, ecological integration, and community relevance. The consolidated results from the literature, field surveys, and interviews are presented in Table 3.

Table 3 Table summary of 3DMARs design criteria, classified by themes and codes

Code	Design criteria category	Qualitative insights	Source
MO	Modularity & Installation	The design must allow easy assembly and disassembly of modular units both vertically and horizontally. Modules should be customizable and constrained to sizes suitable for transport.	(1), (3.2). (3.3)
PA	Physical Aspect	The recommended height of 3DMARs is 0.80–1.20 m to optimize underwater visibility and structural clarity. Well-organized clusters and solid foundations enhance stability.	(2), (3.1)
ST	Structural Stability	Structures must withstand dynamic underwater wave forces. Incorporating open voids enhances water flow and mitigates the impact of waves.	(1), (2), (3.1)
MT	Material & Texture	The use of sustainable materials with rough textures is recommended to support coral attachment and ecological functionality.	(1), (2), (3.1)
PL	3D Printing Process / Limitation	Continuous layering of mortar is preferred. Designs must avoid complex shapes due to technical constraints in 3D printing systems.	(1), (3.1)
EC	Environmental Compatibility	Designs should harmonize with local marine environments in terms of color and texture, mimicking the natural characteristics of reefs.	(1), (2), (3.2)
HC	Habitat Creation	Small holes, crevices, and gaps should be incorporated to encourage marine life settlement and enhance coral larvae attachment.	(1), (2), (3.1), (3.2)
SC	Seascape & Site Conditions	The seabed should be flat and composed of stable ground, free of steep slopes or coral reefs that could hinder installation.	(1), (2), (3.2)
CR	Coral Restoration Integration	Site-specific components, such as coral frames or PVC structures, should be integrated based on local practices and restoration needs.	(1), (2), (3.2)
US	Usability & Transportation	Modules should be lightweight (≤ 20 kg), compact (approx. 35 × 25 cm), and fit standard transport crates. Local transport methods should be considered for logistics.	(1), (2), (3.2), (3.3)

Furthermore, detailed descriptions of each thematic category and its corresponding codes, which influence the design criteria of 3DMARs tailored explicitly for implementation at Koh Khai, Chumphon Province, are elaborated as follows.

- *Modularity Design (MO)*: The modular design enables expansion by connecting multiple stackable modules, allowing for easy assembly and disassembly. The modules are designed to support physical and structural connections that enable both vertical and horizontal expansion as clusters. Simple components, such as PVC pipes, which are widely accessible within the Thai context, are used as interlocking mechanisms between modules.
- *Physical Aspect (PA)*: Each module is designed for vertical stacking, accommodating up to four layers with an optimal height ranging from 1.00 to 1.20 m to enhance underwater visibility. To ensure stability and functionality, the design is based on simple, rectangular geometric forms.
- *Stability (ST)*: The modular arrangement is designed to include voids between assembled modules, ensuring minimal resistance to underwater wave currents. This configuration incorporates crevices, gaps, and openings to mitigate the impact of hydrodynamic forces while providing a stable foundation for the structure during assembly.
- *Material/Texture (MT)*: The 3DMARs are constructed using eco-friendly materials provided by SCG., Co. Ltd. (Siam Cement Group), selected for their compatibility with underwater environments. The rough texture facilitates coral larval attachment, contributing to ecological restoration. Furthermore, the materials have been rigorously tested to ensure their environmental compatibility and long-term performance.

- *3D Printing Limitations (PL)*: The design draws inspiration from the structural forms of marine barrel sponges and lettuce corals, adapting them into simplified shapes optimized for the 3D printing process. This approach minimizes intricate details while prioritizing layered geometries that align with standard 3D printing capabilities.
- *Environmental Compatibility (EC)*: The design of the 3DMARs is inspired by the natural forms of local coral species, including marine barrel sponges and lettuce corals, following from the literature review [67] and survey. The modules feature a brown clay color and a rough surface texture, enabling them to integrate harmoniously with the marine environment of Chumphon Province while mimicking the appearance of natural coral. Their design supports random arrangement, enhancing their ability to blend seamlessly into the underwater habitat.
- *Habitat Creation (HC)*: Inspired by biomimetic design, the 3DMARs incorporate small holes and tunnels, supporting ecological integration and providing shelter for marine creatures. The structure includes gaps and internal voids that promote coral larval attachment and aid in habitat creation.
- *Coral Restoration (CR)*: The 3DMARs incorporate specialized components essential for coral restoration, such as bulb tubers. These features are designed to facilitate coral rehabilitation by enabling the attachment of coral branches, thereby enhancing the restoration process.
- *Usability (US)*: Each module is designed with dimensions compatible with a standard wooden pallet and is divided into sections measuring approximately 35 × 25 cm. (H < 25 cm.), to facilitate manual handling, the weight of each unit is kept under 20 kg, allowing the use of buoyancy aids and significantly reducing installation costs by eliminating the need for cranes. Additionally, small holes are incorporated into the design to secure anchor ropes and reels, ensuring safe and efficient conveyance during installation.

2.5 Ideation phase

2.5.1 Design process of the 3DMARs

As part of the ideation stage within the Design Thinking process, the design of the 3DMARs follows a systematic approach, leveraging computer-aided design (CAD) software to refine design elements, as shown in Table 4. This design phase, which involves experimental design exploration, encompasses multiple iterative steps that systematically integrate various codes derived from established design criteria. Each stage of

Table 4 The table illustrates the code implemented during the design process

Design phase	Design criteria codes	Focus attributes	Description
Preliminary design	MO, PA, ST, MT	Mass, dimensions, depth, height, material, form, modularity	Defines initial geometric and structural characteristics. Emphasizes stability, ease of expansion, rough textures, and the use of sustainable materials to minimize component waste.
Schematic design	US, EC, PL	User interaction, surface detail, environmental integration, printability, installation mechanisms	Refines physical form using a user-centric approach. It incorporates interlocking holes, interior voids, anchor rope attachments, and a biomimetic design that reflects local coral species.
Final design	HC, CR	Habitat formation, coral restoration integration	Finalizes functionality. Introduces sponge-inspired bulb tubers that enhance water flow, provide marine shelter, and facilitate coral branch attachment, thereby promoting biodiversity.

the process is applied methodically, ensuring a principled approach that progressively refines the physical attributes of the 3DMARs.

2.5.1.1 Preliminary design Based on the established design criteria, the codes MO, PA, ST, and MT are applied at this stage to define key attributes, including mass, size, depth, height, shape, material, and other initial characteristics of the workpiece. The design prioritizes sustainability, ensuring no component waste is generated. It is developed from simple geometric forms for stability and allows for seamless expansion into interconnected clusters.

2.5.1.2 Schematic design Guided by a user-centric and problem-solving approach, this phase integrates the codes US, EC, and PL to establish the physical attributes and detailed enhancements of the 3DMARs. The design incorporates features that emulate the natural forms of local coral species while minimizing complexity to accommodate the limitations of 3D printing. Special attention is given to installation methods and interlocking mechanisms, including small holes within each module designed to ensure structural stability. These holes also serve to secure anchor ropes and reels, facilitating the safe conveyance and underwater installation of equipment. As well as the interior void for rubble deployment, which is a technique to facilitate the survival of coral recruits [68].

2.5.1.3 Final design In this phase, the codes HC and CR are employed to refine and enhance the functionality of the 3DMARs in alignment with sustainable environmental principles. A notable feature is the design of the bulb tuber, inspired by the canal system of Porifera sponges, which incorporates interconnected cavities to facilitate water flow and expand habitat spaces for marine life. Additionally, the bulb tuber functions as a connection point for coral branch attachment, supporting further coral restoration initiatives.

AutoCAD, SketchUp, and Rhino software were employed to translate designs into 3D, three-axis printable formats for prototype production. The process began with a comprehensive evaluation of the attributes and physical context of the 3DMARs, followed by an assessment of production feasibility and the limitations of the 3D printing technology. The surface geometry of the structure was then analyzed to calculate the printer's running path. This path was generated using a G-code generator script, which converted it into G-code to operate the three-axis printing device during the 3D printing process. Further details of the preliminary design process are illustrated in Fig. 6, and the final design is illustrated in Fig. 7.

Throughout the design process, codes derived from the design criteria were applied to ensure that the 3DMARs are practical for users, modular in design, and environmentally sustainable. The detailed components of the other 3DMARs, which are classified as indicated in Fig. 8, were also considered. Moreover, the design accounted for the voids between modules during horizontal expansion to mitigate the impact of underwater waves, enhance water flow, and increase the surface area of the structures, thereby promoting coral larval attachment. This approach also aims to improve the marine habitat. Vertical stacking, utilizing a triangular connection format, was implemented to ensure structural stability and achieve an optimal height for the intended purpose, as indicated in Fig. 9.

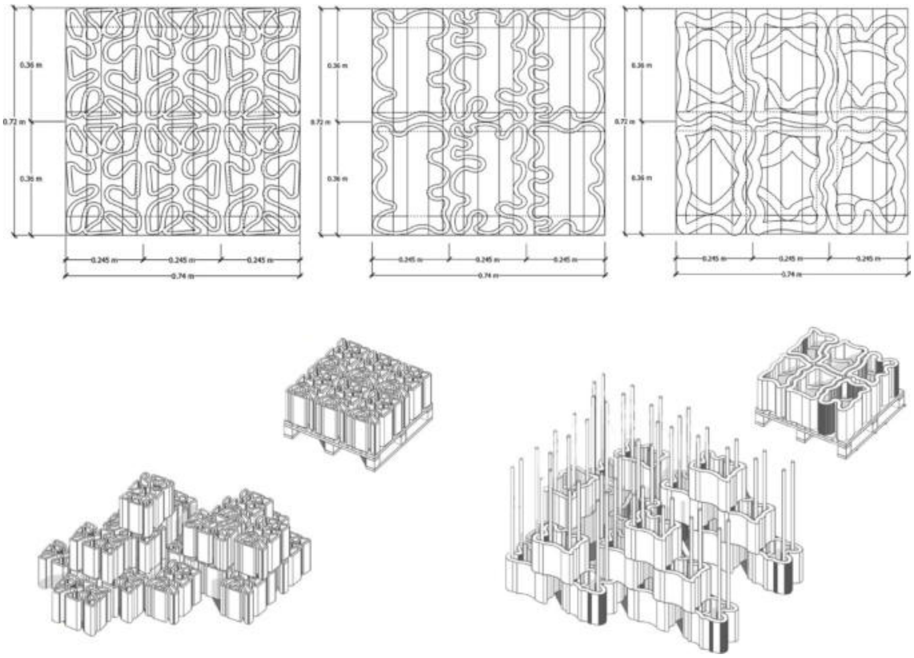

Fig. 6 The preliminary and schematic design of 3DMARs simulated in AutoCAD/Sketchup software

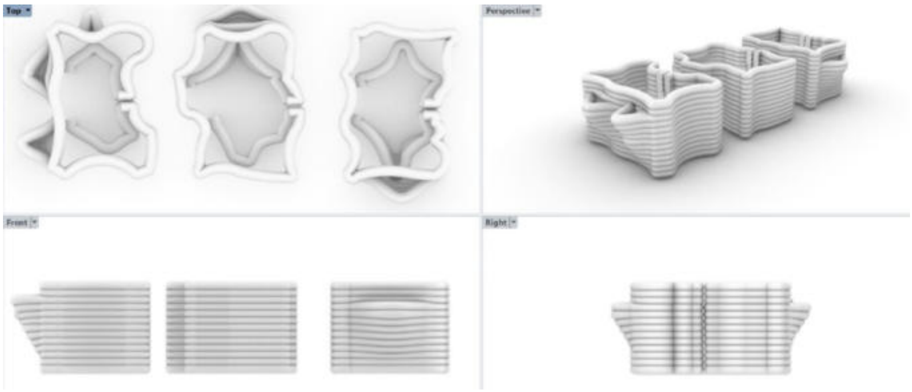

Fig. 7 The final design of 3DMARs was simulated in Rhino software

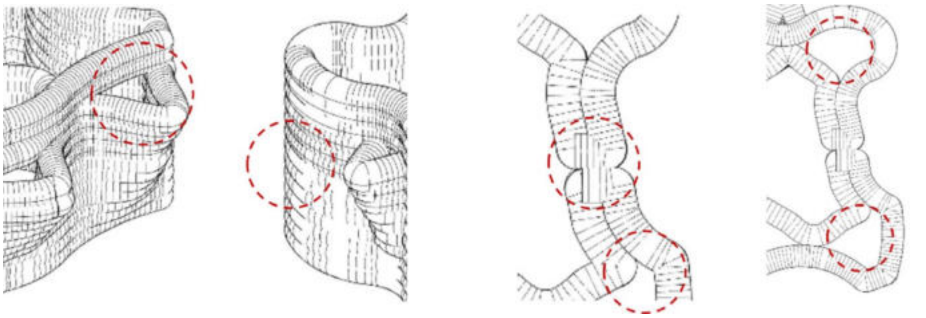

Fig. 8 The image illustrates the detailed components of 3DMARs. Bulb Tuber (left) for coral restoration [CR] and improve marine habitat [HC], Rough layered surface (left center) for enhances coral larval attachment [MT], Gaps (right center) for enhances coral larval attachment [HC], Tuber hole (right) for conveying process [US], connection joint [MO], and improve marine habitat [HC]

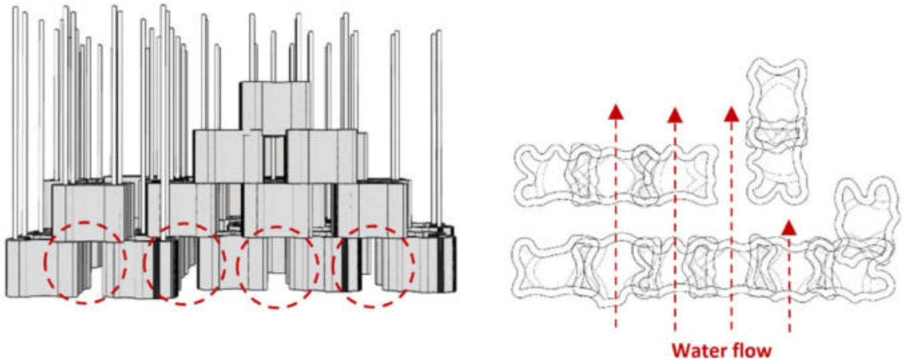

Fig. 9 The left image indicates the Elevation, and the right image indicates the Top view. Overall illustrates the stacking and expansion of 3DMARs with voids for several purposes, such as enhancing water flow and reducing underwater wave impact, triangle format for stability [ST], promoting coral larval attachment and marine habitat [HC]

Installation methods for the 3DMARs were developed using a user-centric, problem-solving approach tailored to address the limitations and contextual factors specific to local coastal communities in Thailand, which often lack access to large-scale equipment typically required for artificial reefs deployment. The conveying and placement procedures were designed to serve as practical guidelines, allowing community individuals to execute installations independently. The proposed methods prioritize minimizing workforce requirements while adhering to underwater safety standards, with expert guidance ensuring effective implementation. Specific roles were designated to streamline operations, such as the Delivery Position, which is responsible for deploying modules from the vessel. Conveying Position: Manages the transportation of modules via anchor ropes from the surface to the seabed. Receiving Position: Arrange the modules into the intended configuration on the seafloor. Coordination Role: Oversees overall operations to maintain workflow and safety compliance.

The deployment process of the 3DMARs modules underwater is facilitated using standard anchor ropes. One end of the rope is securely fastened to a local vessel, while the other end serves as a guide for positioning and stabilizing the structures. This transportation method aligns with the traditional fishing techniques practiced by local fishermen in the region, ensuring familiarity and efficiency in implementation. To achieve precise placement, stability, and buoyancy control, detailed calculations are conducted to determine the optimal number and weight of the modules. These calculations are essential in mitigating potential displacement and ensuring the structural integrity of the deployed units. Each module is equipped with a reinforced hole specifically designed to accommodate anchor ropes and reels, ensuring structural integrity and durability during deployment. Further details on the installation methods and procedural steps are illustrated in Fig. 10.

2.6 Prototyped phase

2.6.1 Prototyped production of the 3DMARs

All prototype modules are produced using a CNC Gantry 2 × 2 3D printing device, supported by SCG Co., Ltd's resources for academic research purposes. Extensive testing was conducted to evaluate various materials for their compatibility with underwater environments, considering factors such as visual integration, weight-to-volume ratio,

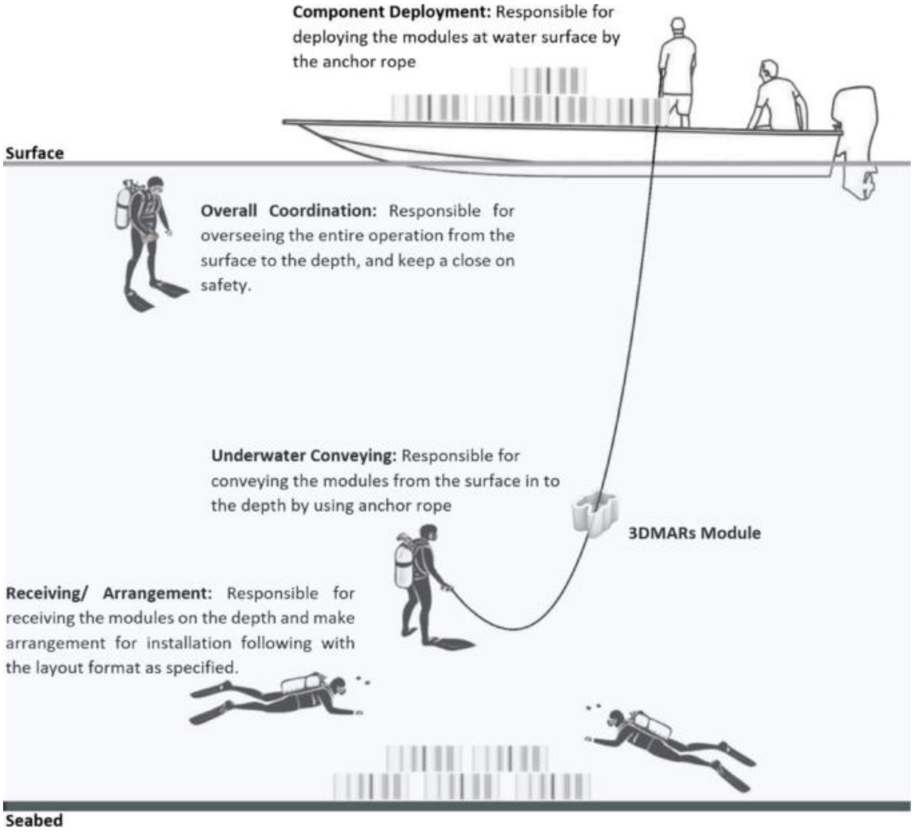

Fig. 10 The diagram illustrates the installation method of 3DMARs

Table 5 Detailed description of the material and 3D printing specifications

3D printing process	Material properties
Printing Layered Time: 3.3 min	Wet Density: 2,000–2,200 kg/m^3
Number of Layers: 13 layers	Dry Density (28 Days): 1,800–1,900 kg/m^3
Total Printing Time: 1.5 h	Compressive Strength (7 Days): >25 MPa
Pump Type: PANMIXER	Compressive Strength (28 Days): >30 MPa
Water Mix Rate: 0.19 L/min	Carbon Footprint: 248 kg/ton
Depth of Printed Line: 3 cm	Carbon Sequestration:–
Printed Head Size: 2.5 cm	Total CO_2 Emission: 248 kg/ton
Speed: 3500	
Motor Speed 2 K:–	
Feed Rate: 108 RPM	
Volume: 58 RPM	
Sinking Distance: 300 RPM	

and buoyancy. The results identified SCG-LW250 LOW CARBON, an eco-friendly material developed by SCG Co., Ltd., as the most suitable option. This material demonstrated excellent underwater compatibility, blending harmoniously with the marine environment while offering optimal weight and buoyancy properties. Detailed specifications of the material and 3D printing process are provided in Table 5; Fig. 11. Experts oversaw the 3D printing process to ensure precision and quality. The modules were designed with sustainability as a key focus, incorporating waste-minimizing strategies and efficient packing solutions. Each workpiece was engineered to fit onto standard wooden pallets, thereby optimizing transportation logistics and simplifying handling. The characteristics

Fig. 11 3D printing process, under supervision from SCG Co., Ltd. 3D-printed experts, Image courtesy of Torpong Limlunjakorn

Fig. 12 3DMARs prototyped and manufactured at SCG factory (left, left center), Isometric view of 3DMARs (right center), Top view of 3DMARs (right), Image courtesy of Torpong Limlunjakorn

of the prototype modules and further details on the production process are depicted in Fig. 12.

2.7 Testing phase

In alignment with the design thinking framework, the testing phase for the 3DMARs prototypes was carried out prior to their deployment at the designated installation site. This phase was essential for refining installation methods and ensuring operational success. The testing concentrated on logistical and transportation considerations, assessed basic usability, and evaluated the buoyancy of each module under controlled conditions to minimize potential risks during actual deployment.

Pilot testing was performed in a 3-meter-deep pool (Fig. 13), using the installation methods previously developed. Modular units were assembled in a triangular configuration, providing a robust foundation connected with PVC tube mechanisms to simulate the planned arrangement. The testing confirmed that the module's physical attributes, such as weight, size, and interlocking capabilities, were compatible with the intended installation procedures. User-centered evaluations conducted during the testing phase played a pivotal role in refining the design to optimize buoyancy, ease of handling, and overall functionality. The results confirmed that the installation methods and modular configurations were both practical and effective, enabling seamless assembly and deployment without errors. This comprehensive testing process not only validated the feasibility and usability of the 3DMARs but also ensured their readiness for successful implementation at the designated site.

3 Result/implementation phase

3.1 Pilot installation of the 3DMARs

The pilot deployment of the 3DMARs was successfully conducted in September 2024 at a shallow reefs site approximately six meters deep off the coast of Koh Khai, Chumphon Province. This milestone provided critical validation of the 3DMARs system's technical feasibility, ecological sensitivity, and community-oriented design. A total of 42 modules, efficiently packed into seven standard wooden pallets, were transported via two locally operated boats, highlighting the system's low logistical demands and its compatibility with the readily available infrastructure in coastal communities.

Unlike conventional artificial reefs installations, which often require large vessels, cranes, and professional crews, the 3DMARs were deployed entirely by local volunteers and community members using only freediving and basic SCUBA techniques. No specialized equipment was necessary, further emphasizing the design's accessibility. The deployment site was selected through consultations with marine experts and local stakeholders. Following the installation method, each module was lowered manually into position using a buoyancy-controlled rope system, enabling precise placement without the need for mechanical tools. Pre-integrated holes and PVC interlocking components ensured secure horizontal and vertical alignment on the seabed.

The entire installation process was completed in under two hours, substantially faster than conventional artificial reefs, demonstrating both operational efficiency and the intuitive nature of the modular system. The modules' textured surfaces, environmentally responsive coloration, and structural complexity were intentionally designed to promote coral larval settlement, habitat diversity, and aesthetic integration with the local benthic

Fig. 13 logistic / transportation process (left), sustainable logistics (left center), testing operation of 3DMARs in pool (right center), triangular arranged format underwater (right), Image courtesy of Torpong Limlunjakorn

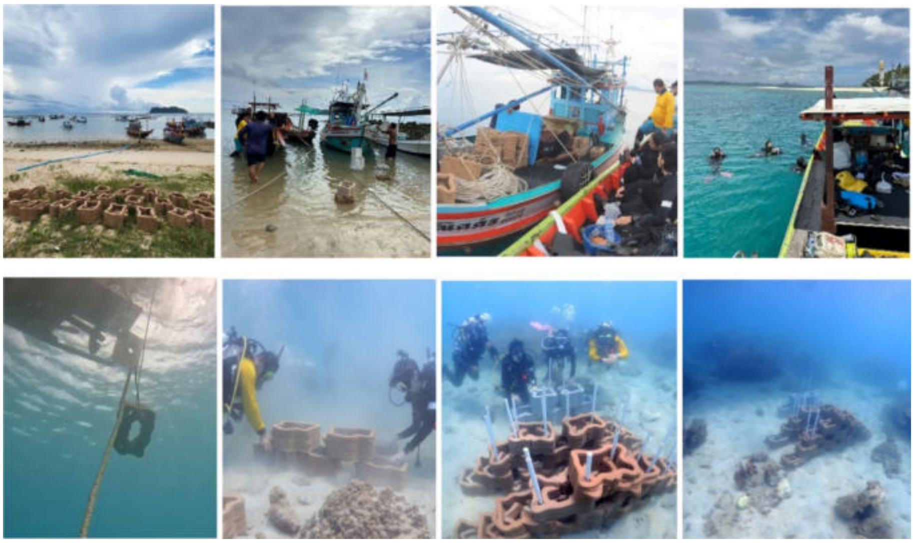

Fig. 14 Installation operation at Koh Khai by procedure of operation, from coast to water surface (top left to right), from water surface to underwater seabed (bottom left to right), Image courtesy of Torpong Limlunjakorn

Fig. 15 Physical characteristics of the 3DMARs while installing (left to right), Image courtesy of Torpong Limlunjakorn

environment (Fig. 14). Notably, the modular dimensions were optimized for efficient stacking and transportation on small vessels, thereby further reducing logistical costs and environmental impact. Community members reported that the ability to participate directly in the installation process was accessible and manageable, reinforcing the system's potential to support local stewardship and encourage sustained involvement in marine conservation. This pilot deployment demonstrates that 3DMARs are not only technically viable but also offer a replicable, low-cost, and inclusive model for aquatic habitat restoration (Fig. 15). By lowering barriers to participation and enabling community-led implementation, the system exemplifies how design innovation can democratize ecological restoration in resource-constrained coastal regions. However, certain design functions have not yet been fully utilized, such as the bulb tuber and the holes intended for attaching staghorn coral fragments for coral rehabilitation, which have so far served only deployment purposes. Nevertheless, the internal voids intentionally incorporated within each module have been filled with rubble to create additional cavities, which are essential for providing habitats for marine organisms.

Following installation, underwater physical data were collected using a three-dimensional photogrammetry technique, which captures both the geometric and visual properties of submerged structures to generate accurate 3D models [69–70]. This process produced a high-resolution digital twin of the 3DMAR deployment site, offering detailed

Fig. 16 Top view of UW photogrammetry method (left), Perspective view of UW photogrammetry method (center, right)

Fig. 17 Photographic evidence shows initial biological colonization. Image courtesy of Torpong Limlunjakorn

documentation of physical attributes, material composition, surface textures, and spatial configuration (Fig. 16). The model not only captures the exact positioning and modular assembly of the reef structures but also provides an immersive representation of the surrounding underwater environment, facilitating interpretation for stakeholders who cannot access the site directly (see 3D model in[2]).

Moreover, the 3D model serves as a valuable tool for marine researchers, enabling the observation of temporal changes at the pilot scale, such as site-specific arrangements, coral attachment, and biological colonization. It supports ongoing monitoring by enhancing spatial understanding of the interactions between artificial structures and natural reef systems, ultimately contributing to more accurate ecological assessments and informing adaptive design strategies for future deployments.

Approximately six months after installation, a preliminary underwater survey (May 2025) was conducted to assess the early ecological response of the 3DMARs. Some modules were displaced by monsoonal wave activity, indicating the need to improve anchoring or interlocking mechanisms. Despite this, photographic evidence, shows initial biological colonization, including widespread algal turf and biofilm pioneer species that promote further settlement (Fig. 17). Early-stage sessile invertebrates such as colonial tunicates, hydroids, and polychaete tubes were also observed, contributing to microhabitat complexity and indicating the onset of ecological succession [71]. Additionally, the internal voids of the 3DMARs, intentionally designed to accommodate

---

[2] https://weshape-gs.wedolabs.net/viewer?target=https://pub-398a6cc485f94358a98c6997e7de7c5b.r2.dev/files/d1030234-8132-11ef-96e6-0242ac130002.ply.

Fig. 18 Photographic evidence shows the initial marine habitat. Image courtesy of Torpong Limlunjakorn

rocks or rubble, create multiple cavities that provide shelter for various marine organisms. Observations during initial assessments revealed the presence of crustaceans and mollusks within these internal spaces, supporting the modules' potential as multifunctional habitats (Fig. 18). Juvenile damselfish, known for their territorial behavior and adaptability, were among the first fish to inhabit the structures [72], commonly observed around the 3DMARs. These preliminary findings, conducted by the researcher in the dual role of designer and conservation-trained diver rather than as a professional marine biologist, suggest promising outcomes in terms of structural integrity, habitat provision, and material compatibility within the aquatic environment.

4 Discussion

4.1 Possible explanation

This study tested the hypothesis that a modular, small-scale 3D-printed artificial reef systems designed through a user-centric approach can balance ecological effectiveness with operational efficiency under Thailand's local constraints. Unlike conventional large-scale digital fabrication reefs that require specialized equipment and large crews [73–74], the structures range in height from approximately 80 to 120 cm and in weight from around 250 to 400 kg. Conversely, the 3DMARs system was developed as an accessible, community-deployable environmental product. The design criteria focused on manageable unit weight (under 20 kg), ease of handling, transport, installation in shallow waters (> 12 m), inter-module connectivity, and compatibility with local resources. Ecological considerations included forms suitable for the surrounding marine environment, coral rehabilitation features, flow-through voids, rough-surfaced materials, and internal cavities for marine habitats [75], tailored to Thai marine conditions.

Pilot operations showed that local community groups, Ban Hin Kob community in Chumphon Province, could successfully deploy the 3DMARs using only two small fishing boats. Monitoring indicated positive results in coral larval settlement and marine biodiversity enhancement. However, as with prior studies, ecological outcomes are influenced by factors such as site location, depth, seasonality, and local biodiversity [76]. While these controlled trials provide a model for community-driven deployment, broader application would require further site-specific adaptation and investigation. These findings suggest possible explanations and serve as a foundation for future research aimed at refining both operational and ecological aspects of modular artificial reef systems.

4.2 Cost of logistics and deployment

From previous studies, traditional artificial reef systems in Southeast Asia, including Thailand, commonly involve the deployment of large concrete modules using heavy vessels, leading to substantial logistical expenses [71–72]. For example, Thailand's Department of Marine and Coastal Resources deployed 13,658 reef modules in 2019 at a total cost of approximately USD 2.6 million (USD 192 per unit) [77], while India's Tamil Nadu deployed 200–300 modules between 2023 and 2024 at USD 138 per unit, and Malaysia's anti-trawling reef program (2021–2023) spent USD 260,000 for 57 units, averaging USD 4,561 per structure [78]. These figures highlight cost barriers for small community-led initiatives. In contrast, the 3DMARs prototype features a low-impact deployment, being compact, modular, and manually deployable using small-scale coastal fishing boats. According to the survey, these boats typically charge around USD 150 per trip and can accommodate up to 100 units per load. This approach significantly reduces logistical burdens and enables broader community participation, particularly in shallow coastal zones, which heavy vessels cannot access, where Thailand's reefs are commonly located. Moreover, the 3DMARs design was based on standard pallet dimensions to optimize transport and handling. Using strong 3D-printed concrete allows the units to be stacked securely, making deployment more practical compared to the conventional Ars, which is unable to stack while logistic. It reduces the need for large trucks, allowing transportation using only small six-wheel trucks, thereby lowering land shipping costs.

Additionally, the modules can be loaded and deployed pallet by pallet, enhancing logistical efficiency. This approach differs from other large-scale artificial reef projects in Thailand and globally [30, 31, 73–74], where larger and heavier 3D-printed structures often pose logistical challenges. From a design perspective, the concept of modularity developed in this study offers a reference framework for reducing transportation and installation costs associated with large-scale ecological structures [33]. It highlights how modular design can contribute not only to structural flexibility but also to improving the practicality and scalability of Thai context logistics and deployment efforts.

4.3 User-centered implementation and community participation

Many large-scale artificial reef projects globally, such as Reef Design Lab's MARS in Australia and Dubai's 20,000-unit Reef Initiative, require diver-assisted deployment and centralized logistics [74, 79] and rely on high-cost materials, centralized manufacturing, or high-tech joint assemblies [38–40]. The previous conventional ARs projects in the Thai context, which often limit opportunities for direct community involvement [80], where financial and resource constraints, as well as shallow reef conditions, such as those around Koh Khai, necessitate alternative approaches. As a result, this study was deliberately developed following a user-centered, community-operable design philosophy according to Don Norman, the Design Thinking approach [81]. The 3DMARs attribute is tailored explicitly for self-deployment by small groups, including NGOs, coastal communities, and academic institutions, without reliance on heavy machinery, limited technical and financial capacity. Physical design considerations, such as modularity, stackability, and ease of handling, were integrated from the outset to reduce required manpower and enable deployment using only basic tools like fishing ropes. The use of smaller, modular, and more affordable units can improve accessibility at both community and individual levels, fostering broader participation in marine restoration efforts. From a design perspective and hypothesis, if artificial reefs are regarded as a form of product, both physical characteristics and user interaction under local constraints should be considered alongside several factors in a specific location. Similarly, the 3DMARs demonstrate site-specific adaptability, modular expandability, and improved ecological functionality, which perform effectively in shallow coastal waters adjacent to local communities at Koh Khai. This perspective implies that 3DMARs design solutions may vary across different regions.

4.4 Design strategy and environmental adaptation

Global traditional ARs projects often focus on single-function goals such as fish aggregation or coastal protection [82]. Similarly, in Thailand, which commonly uses conventional cubic concrete frames, implemented to focus on deeper waters (depth > 10 m) [83], and huge 3D printing Artificial Reefs as physical aspects which focus only mimicking local coral forms [84], which are typically designed with a focus on structural mass and coral settlement surfaces [81, 85]. However, there is often a lack of internal voids and ecological complexity.

In contrast, the 3DMAR initiative aims for multifunctionality, supporting coral attachment, fish habitats, and adding void space to support marine behavior [86]. The design also aimed to maximize surface area to enhance coral larval settlement and to operate in shallow-water environments. Also, 3DMARs attribute is designed to have interior space for deploying rocks inside for marine habitat and coral recruit improvement. According to the literature [87, 88], deploying rocks or other rigid substrates over the rubble can facilitate the survival of recruits. Small modular structures can be used at multiple scales, with or without attached coral fragments, to create structural complexity and settlement surfaces. It aligns with projects like RRREEFS in the Philippines, which also prioritize habitat complexity and modularity [40], however, these projects require a connection joint or detailed mechanism for assembly underwater. While 3DMARs are embedding co-design with local stakeholders, considering Thai context limitations, which leads to a reduced process of assembly. The utilization of the Design Thinking framework, incorporating iterative prototyping, ergonomic testing (onshore and underwater). Adaptation to Thailand's monsoon-driven currents and sediment movement requires designs that withstand hydrodynamic stresses. Similar to Japan's permeable submerged breakwaters and Eco-reef modules, incorporating internal voids and open spaces helps reduce wave pressure while ensuring structural stability [68].

Additionally, the modules were visually and morphologically adapted to mimic native coral forms, enhancing ecological integration, instead of using the geometric cubic aspect. However, artificial reef production using digital fabrication, including 3D printing technology in Thailand, still faces several limitations. Most production relies on CNC gantry 2 × 2 machines with a line thickness of approximately 2–3 cm, restricting the creation of more intricate and complex forms. The development of alternative materials such as ceramics, resins, or other advanced composites, already applied in international projects, could offer new possibilities for diversifying artificial reefs design in Thailand, particularly in creating porous or three-dimensional lattice structures to enhance marine habitat potential.

4.5 Effectiveness for coral restoration and marine recreation

Underwater monitoring conducted during the six months following deployment revealed early signs of ecological effectiveness. However, several studies suggest that ecological succession on artificial reefs is influenced by multiple complex factors, making consistent patterns difficult to establish [89]. Among variables such as time since deployment, distance from natural reefs, and seafloor depth, only depth has shown potential as a significant factor [90]. Further adaptations could enhance artificial reef designs in Thailand by incorporating insights from close ecological observations of native marine species within surveyed areas. For instance, crabs and mollusks typically inhabit small cavities and crevices, seeking shelter from predators and strong currents [91]. Sea slugs (nudibranchs) prefer sheltered, complex surfaces where they can graze on sponges and sessile invertebrates [92]. At the same time, seahorses (Hippocampus spp.) require vertical or branched structures for holdfast anchoring due to their poor swimming ability and cryptic behavior [93]. Integrating species-specific habitat preferences into internal void design and reef typologies can enhance 3DMARs' habitat complexity beyond coral settlement, supporting multifunctional artificial reefs that accommodate diverse marine life and contribute to broader ecosystem restoration.

Additionally, the design integrates porous structures and rough surface textures, which simultaneously enhance habitat availability for small marine species and support higher coral larvae settlement rates [94], thereby promoting more effective ecological integration. Additional elements, including substrate texture and coral species-specific settlement preferences, also play critical roles in shaping colonization dynamics [95]. Furthermore, previous studies indicate that coral larvae tend to settle more successfully on natural coral substrates compared to artificial surfaces [96, 97]. The incorporation of calcium carbonate or similar bioactive materials into artificial reef structures has been shown to enhance larval settlement rates and promote early-stage coral growth by improving surface chemistry and mimicking natural reef conditions [98]. In this study, pre-mixed concrete formulations from SCG were applied; however, further localized investigations are necessary to assess variations in settlement success across different depths, sites, and coral species specific to each area.

In comparison, conventional coral restoration methods in Thailand, using repurposed materials such as PVC pipes, steel frames, fishing nets, or concrete blocks [22–25, 82], may offer lower material costs due to the reuse of existing structures [83, 84]. However, these approaches often require specialized skills for underwater assembly and may necessitate training to transfer specific technical knowledge and equipment such as sand screws, stocking platform, and coral tree [99–101]. In contrast, the 3DMARs system emphasizes digitally fabricated modular units designed to minimize manual assembly processes. Deployment and the coral restoration process involve only transportation and placement underwater, without complex in-situ construction. Furthermore, the design is intended to support scalable, large-quantity production while maintaining ease of use and consistency across different deployment contexts.

5 Conclusion

This study demonstrates Thailand's first design-led development and community-driven deployment of modular 3D-printed artificial reefs (3DMARs) at Koh Khai, Chumphon Province. By applying Design Thinking, the project established adaptable, user-friendly, and ecologically effective reef structures suitable for local capacities. The 3DMARs prototype offers both functional habitat benefits and a transferable framework for broader application across Thailand's varied coastal contexts. The outcomes emphasize modularity as a critical principle, enabling reef structures to be scaled down from conventional sizes and tailored for specific sites. Beyond replicating coral morphology for ecological compatibility, future development should consider enhancing coral larval settlement rates through surface material innovation and internal spatial design that supports diverse marine life habitats. Further refinements may include improving connection mechanisms, transport logistics, and inter-module attachment systems, ensuring the reef units remain functional, adaptable, and community-operable across Thailand's varied marine environments.

Acknowledgements
I want to extend our gratitude to the SCG CPAC Green Construction Department for providing 3D printing resources and technical expertise throughout the project. I also thank the Department of Marine and Coastal Resources for their assistance in site selection and obtaining installation permissions, as well as for all their guidance. Moreover, I am deeply grateful to the community members of Ban Hin Kob in Chumphon Province for their unwavering support and collaboration, which proved invaluable to the project's success.

Author contributions
Author A. (Main Auther, Torpong Limlunjakorn) confirms that conducted all aspects of this study, including conceptualization, methodology, data collection, analysis, writing, and manuscript review.

Funding
This research was funded by an Academic Scholarship from the Faculty of Architecture, Art, and Design at King Mongkut's Institute of Technology Ladkrabang for Fiscal Year 2024. The study was supported by a Research Project Grant under Contract No. 2567-02-02-001, titled "The Designing of 3D-Printed Modular Artificial Reef through Design Thinking Framework: A Case Study in Koh Khai, Chumphon Province, Thailand".

Data availability
The design files, CAD drawings, SketchUp models, Rhino models, G code file for 3D printing, and supporting visual materials generated during this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

The need for ethical approval was waived by the Human Research Ethics Committee of King Mongkut's Institute of Technology Ladkrabang (KMITL) (Approval ID: EC_KMITL_68091), as the research involved non-human subjects and did not require ethical review. This study focused on the design of artificial coral reefs and did not involve vulnerable populations, clinical trials, animal testing, or any procedures requiring ethical oversight. All contributors and participants provided informed consent. The research was conducted responsibly, following ethical standards and professional guidelines, utilizing non-intrusive methods and publicly available data.

Competing interests

The authors declare no competing interests.

Received: 29 March 2025 / Accepted: 25 July 2025

References
1. Bracho-Villavicencio C et al. Artificial reefs around the world: a review of the state of the art and a meta-analysis of its effectiveness for the restoration of marine ecosystems. Environments. 2023.
2. Paxton AB, Shertzer KW, Bacheler NM, Kellison GT, Riley KL. Meta-analysis reveals artificial reefs can be effective tools for fish community enhancement but are not one-size-fits-all. Front Mar Sci. 2020;7:282.
3. Boakes Z, Hall A, Jones G, Prasetyo R, Stafford R, Yahya Y. Artificial coral reefs as a localised approach to increase fish biodiversity and abundance along the North Bali coastline. AIMS Geosci. 2022;8(2):303–25.
4. Rowland AJ, Lemasson AJ, Matthews AC, Tweedley JR, Campbell LL. Structural and functional improvements of coastal ecosystem based on artificial oyster reef construction in the Bohai sea, China. Front Mar Sci. 2022;9:829557.
5. Lima JS, Zalmon IR, Love M. Overview and trends of ecological and socioeconomic research on artificial reefs. Mar Environ Res. 2019;145:81–96.
6. Paxton AB, Steward DN, Harrison ZH, Taylor JC. Fitting ecological principles of artificial reefs into the ocean planning puzzle. Ecosphere. 2022;13(2):e3924.
7. Pancrazi I, Feairheller K, Ahmed H, Di Napoli C, Montefalcone M. Active coral restoration to preserve the biodiversity of a highly impacted reef in the Maldives. Diversity. 2023;15(9): Article 1022. https://doi.org/10.3390/d15091022.
8. Bracho–Villavicencio C, Matthews–Cascon H, Rossi S. Artificial reefs around the world: a review of the state of the art and a meta-analysis of its effectiveness for the restoration of marine ecosystems. Environments. 2023;10(7):121. https://doi.org/10.3390/environments1007012.

9. Paxton AB, Steward DN, Mille KJ, et al. Artificial reef footprint in the united States ocean. Nat Sustain. 2024;7:140–7. https://doi.org/10.1038/s41893-023-01258-7. (accessed on 15 May 2025).
10. Seaman W. Design, siting, engineering, construction, and evaluation of human-made reefs. In: Steele JH, editor. Structure in the sea. 2023:147–204. Elsevier. https://doi.org/10.1016/b978-0-12-823425-9.00001-1. (Accessed 2025 Jun 13.).
11. Theparoonrat Y, Manajit N, Yingyuad W, Amornpiyakrit T, Tanvilai R, Suksamran N, Environmental survey studies on artificial reefs in Rayong Province, Thailand: technical assistance in a pilot site for suitable designs of resource enhancement practices. In: Proceedings of the symposium on strategy for fisheries resources enhancement in the Southeast Asian Region;, Pattaya et al. Thailand. Southeast Asian Fisheries Development Center; 2016. pp. 1–10.
12. Frau F, Murana S, Marras M, Tuzzolino M, Abis A. SATURN to defend the Mediterranean from illegal bottom trawling. Med-Sea Foundation; 2022 Nov 18. https://www.medseafoundation.org/index.php/en/news-eng/698-antitrawling-marine-protected-area-sardinia
13. Tesorero A. Dubai: first of 20,000 reefs that can last over a century deployed off the city's coast. Khaleej Times. 2024 Nov 23 [cited 2025 Jul 8]. https://www.khaleejtimes.com/uae/environment/dubai-first-of-20000-reefs-that-can-last-over-a-century-deployed-off-the-citys-coast
14. Great Barrier Reef Marine Park Authority. Green Island reef rehabilitation project. Townsville (QLD): GBRMPA. 2024 Feb 1 [cited 2025 Jul 8]. https://www2.gbrmpa.gov.au/our-work/field-management/green-island-reef-rehabilitation-project
15. Department of Climate Change. Energy, the Environment and Water. Stars reef rehabilitation: case studies. Canberra (ACT): Australian Government; [cited 2025 Jul 8]. https://www.dcceew.gov.au/parks-heritage/great-barrier-reef/protecting/case-studies/stars-reef-rehabilitation
16. Fadli N, Campbell SJ, Ferguson K, Keyse J, Rudi E, Riedel A, et al. The role of habitat creation in coral reef conservation: a case study from Aceh, Indonesia. Oryx. 2012;46(4):501–7.
17. Hussein KB, Bensahla-Talet L, Chakouri A. First Algerian artificial reef O.R.1 in Oran coastline: construction, immersion and scientific monitoring. Maritime Technol Res. 2025;7(3):275189. https://doi.org/10.33175/mtr.2025.275189.
18. Department of Marine and Coastal Resources, Ministry of Natural Resources and Environment. Information on Coastal Marine Resources in Chumphon Province: Manual Book. DMCR Publishing. 2018. https://www.dmcr.go.th/detailLib/3759 (accessed on 9 December 2024).
19. Phongsuwan N, Chankong A, Yamarunpatthana C, Chansang H, Boonprakob R, Petchkumnerd P, Thongtham N, Paokantha S, Chanmethakul T, Panchaiyapoom P, Bundit O-A. Status and changing patterns on coral reefs in Thailand during the last two decades. Deep Sea Res Part II. 2013;96:19–24. https://doi.org/10.1016/j.dsr2.2013.02.015.
20. Chulalongkorn University Academic Service Center. Case study: Chulalongkorn University showcases two innovations for reviving Thai corals. http://www.sustainability.chula.ac.th/th/report/2055/ (accessed on 9 December 2024).
21. Southeast Asian Fisheries Development Center. Regional guidelines on indicators for sustainable management of fisheries refugia in the South China Sea and Gulf of Thailand [Internet]. Samut Prakan (TH): SEAFDEC; 2022 [cited 2025 May 9]. https://repository.seafdec.org/handle/20.500.12066/6877
22. Sutthacheep M, Yeemin T, Saenghaisuk C. 3D printing technologies for coral restoration in the Gulf of thailand: A sustainable solution to marine degradation. Volume 19. Environmental Technology & Innovation; 2020. p. 100914.
23. Global Reef. Our Marine Conservation Projects In Thailand. Global Reef; [cited 2025 Jun 13]. https://global-reef.com/pages/projects
24. Thongsamui A, Pharatnchotisakul M, Mekhora T, Kaenmanee M. Economic and social impacts of artificial coral reef deployment on local fishermen in Lang Suan district, Chumphon Province. King Mongkut's J Agric. 2016;34(3):48–60.
25. Chevron Thailand. Artificial reefs converted from retired platform jackets proven to help restore Thai marine ecosystems. https://thailand.chevron.com/en/news/latest-news/2022/progress-of-rigs-to-reefs. Accessed 9 Dec 2024.
26. Charoen Pokphand Group (C.P. Group). C.P. Group launches SEACOSYSTEM: For the Sustainable Thai Sea, integrating support from all sectors for the conservation of Thailand's sea and partners with the Department of Fisheries to plant 1000 artificial reefs. Bangkok: Charoen Pokphand Group (C.P. Group); 2019 Sep 13 [cited 2025 Jul 10]. [https://www.cpgroupglobal.com/en/newsroom/news/132/cp-group-launches-seacosystem-for-the-sustainable-thai-sea-integrating-support-from-all-sectors-for-the-conservation-of-thailand-s-sea-and-partners-with-the-department-of-fisheries-to-plant-1000-artificial-reefs]
27. Monchanin B, Sornkliang T, Reungsamran P, Peerapornpisal Y. Contrasting coral community structures between natural and artificial substrates at Koh tao, Gulf of Thailand. Mar Environ Res. 2021;172:105505.
28. Kheawwongjan A, Kim D-S. Present status and prospects of artificial reefs in Thailand. Ocean Coast Manag. 2012;57:21–33. https://doi.org/10.1016/j.ocecoaman.2011.11.001.
29. Le Cornu E, Rojas C, Matsuda SB, et al. Building better reefs: 3D-printed reef substrates enhance the growth of natural coral reef communities. Front Mar Sci. 2021;8:665310. https://doi.org/10.3389/fmars.2021.665310.
30. Thai Union, Union T, Foundation EA, and SCG join hands for second year of deliver coral reef restoration project. Bangkok: Thai Union; 2024 Dec 4 [cited 2025 Jul 10]. [https://www.cpgroupglobal.com/en/newsroom/news/132/cp-group-launches-seacosystem-for-the-sustainable-thai-sea-integrating-support-from-all-sectors-for-the-conservation-of-thailand-s-sea-and-partners-with-the-department-of-fisheries-to-plant-1000-artificial-reefs]
31. The New Heaven Reef Conservation Program (NHRCP) on Koh Tao. Ocean solutions through coral farms for Thailand's restoration. https://newheavenreefconservation.org/projects/coral-nursery-artificial-reef. Accessed 9 Dec 2024.
32. Higgins E, Metaxas A, Scheibling RE. A systematic review of artificial reefs as platforms for coral reef research and conservation. PLoS ONE. 2022;17(1):e0261964. https://doi.org/10.1371/journal.pone.0261964.
33. Maslov D, Cruz F, Pinheiro M, Pereira EB. Functional conception of biomimetic artificial reefs using parametric design and modular construction. J Mar Sci Eng. 2022;12(9):1682.
34. Goad A. Modular artificial reef structure. Everyday Futures [Internet]. New South Wales, Australia: National Museum of Australia; 2023 [cited 2025 Jul 13]. Everyday Futures. [https://everydayfutures.nma.gov.au/project/modular-artificial-reef-structure/?utm_source=chatgpt.com]
35. Vogler V. A new framework for artificial coral reef design. Bauhaus-Universität Weimar. 2022. https://doi.org/10.14627/537724050.
36. Norris BK, et al. Designing modular, artificial reefs for both coastal defense and coral restoration. Coast Eng. 2025;199. https://doi.org/10.1016/j.coastaleng.2025.104742. Article 104742.

37. Zhao X, Chen W, Xie. L. 3D-printed coral-inspired structures for marine ecosystem recovery. J Environ Manag. 2020;273:111–20.
38. Topotheque. Yfalos reef: modular artificial reef system for biodiversity and coastal resilience. 2023. Retrieved from https://www.topotheque.com/yfalos
39. Reef Design Lab. 3DMARs: Modular artificial reef system using 3D-printed ceramic components. 2022. Retrieved from https://www.reefdesignlab.com/projects/mars/
40. RRREEFS. RRREEFS: A modular reef restoration system combining architecture, marine science, and community engagement. 2024. Retrieved from https://www.rrreefs.com
41. Brown CJ, Lynam CP, Green AJ, et al. Corresponding planktivore and predator spatial distributions in an oceanic coral reef system. Coral Reefs. 2024;43(2):345–57. https://doi.org/10.1007/s00338-024-02514-8.
42. Sherman KD, Gomez MI, Kemenes T, Dahlgren CP. Spatial and Temporal variability in Parrotfish assemblages on Bahamian coral reefs. Diversity. 2022;14(8):625. https://doi.org/10.3390/d14080625.
43. Xie F. Artificial reefs: enhancing fishery resources and habitat restoration. J Fish Res. 2024;8(4):225. https://doi.org/10.35841/aajfr-8.4.225.
44. Glarou M, Zrust M, Svendsen JC. Using artificial-reef knowledge to enhance the ecological function of offshore wind turbine foundations: implications for fish abundance and diversity. J Mar Sci Eng. 2020;8(5). https://doi.org/10.3390/jmse8050332.
45. Daniel JP, Jeremy TC, Chelsea MW. Theory, practice, and design criteria for utilizing artificial reefs to increase production of marine fishes. Front Mar Sci. 2022;9. https://doi.org/10.3389/fmars.2022.983253.
46. Perricone V, Mutalipassi M, Mele A, Buono M. Nature-based and bioinspired solutions for coastal protection: An overview among key ecosystems and a promising pathway for new functional and sustainable designs. ICES J. Mar. Sci. 2023, 80(5). https://doi.org/10.1093/icesjms/fsad080 (Accessed on 9 December 2024).
47. Vivier B, et al. Marine artificial reefs: A meta-analysis of their design, objectives, and effectiveness. Glob Ecol Conserv. 2021.
48. Levenstein MA, Gysbers DJ, Marhaver KL et al. Millimeter-scale topography enables coral larval settlement in wave-driven oscillatory flow. BioRxiv. 2022;2022.03.10.483786.
49. Boström–Einarsson L, Shaver EC, Camitta–Kubo D, et al. An evaluation tool for assessing coral restoration efforts. Front Mar Sci. 2024;11:1404336. https://doi.org/10.3389/fmars.2024.1404336.
50. Lange ID, Razak TB, Perry CT, Maulana PB, Prasetya ME, Irwan T. Lamont AC. Coral restoration can drive rapid reef carbonate budget recovery. Curr Biol. 2024;34(6):1341–8. https://doi.org/10.1016/j.cub.2024.02.009.
51. Monetti FM, Lundström A, Maffei A. Barriers to adopting design for assembly in modular product architecture: development of a conceptual model through content analysis. arXiv. 2024 Nov 26. https://arxiv.org/abs/2411.17768
52. Ambrogi F, Melis C, Manzi A. 3D printing for coral reefs: a review of methods, applications, and benefits. Mar Environ Res. 2021;168:105301. https://doi.org/10.1016/j.marenvres.2021.105301.
53. Brusoni S, Henkel J, Jacobides MG, et al. The power of modularity today: 20 years of 'design rules'. Ind Corp Change. 2023;32(1):1–10. https://doi.org/10.1093/icc/dtac054.
54. Pham LT, Huang JY. 3D printed artificial coral reefs: design and manufacture. Low-Carbon Mater Green Constr. 2024;2(1):23–35.
55. Zhou Y, Li X, Smith A, Chen Z, Wang J. Waste-derived geopolymers for artificial coral development by 3D printing. J Sustain Metall. 2025;11(2):114–25.
56. Chansue N et al. 3D innovareef: sculpture to restore Thai marine ecosystem [Internet]. Chulalongkorn University press release; 2022 [cited 2025 Jul 13]. Available from: 3D Innovareef is not too large, lightweight, and can be carried by anyone thus saving transportation costs.
57. Chulalongkorn University. 3D Printed cement coral: printing a house for fish, create a garden for the ocean [Internet]. Bangkok: Chulalongkorn University. 2022 [cited 2025 Jul 13]. https://www.research.chula.ac.th/3d-printed-cement-coral-printing-a-house-for-fish-create-a-garden-for-the-ocean/
58. Funk JL. Technology change and the rise of new industries. Winning the Future; Routledge,; 2017.
59. Department of Marine and Coastal Resources. (2021, February 18). Coral reef status survey at Koh Khai, Chumphon Province [DMCR report; https://www.dmcr.go.th/].
60. Rangseethampanya P, Yeemin T, Suthacheep M, Suebpala W, Plaeng-ngan P. Assessing coral reef fish biomass at Ko Khai nok, the Andaman sea. Marine Biodiversity Research Group, Department of Biology, Faculty of Science, Ramkhamhaeng University; Khao Lampi-Hat Thai Mueang National Park, Phang Nga, Thailand.
61. Norman DA. Design for a better world: meaningful, sustainable, humanity centered. Cambridge MIT Press; 2023.
62. Ystgaard KF, Atzori L, Palma D, Heegaard PE, De Moor K. Review of the theory, principles, and design requirements of human–centric internet of things (IoT). J Ambient Intell Hum Comput. 2023;14(4):2827–59. https://doi.org/10.1007/s12652-023-04539-3.
63. Han S, Adams J, Hudson S, et al. Methods and operational aspects of human–centred design into research processes for individuals with multiple chronic conditions: a survey study. Nurs Open. 2023;10(1):nnn–nnn. https://doi.org/10.1002/nop2.1554.
64. Mayring P. Qualitative content analysis: a step-by-step guide. 3rd ed. Thousand Oaks, CA: SAGE; 2021.
65. Grzyb K, Konecki K. Qualitative content analysis—a research method in social science. PBE. 2023;32:49–64. https://doi.org/10.12775/PBE.2023.032.
66. Manic Z. Performing qualitative content analysis. Sociologija. 2020;62(1):105–23. https://doi.org/10.2298/soc2001105m
67. Department of Marine and Coastal Resources, Ministry of Natural Resources and Environment. A guide to classifying coral species in Thai waters: Manual Book. DMCR Publishing. 2018. https://www.dmcr.go.th/detailLib/6726 accessed on 9 December 2024).
68. Ceccarelli DM, McLeod IM, Boström-Einarsson L, Bryan SE, Chartrand KM, Emslie MJ, Gibbs MT, Gonzalez Rivero M, Hein MY, Heyward A, Kenyon TM, Lewis BM, Mattocks N, Bay LK. Substrate stabilisation and small structures in coral restoration: state of knowledge, and considerations for management and implementation. PLoS ONE. 2020;15(10):e0240846. https://doi.org/10.1371/journal.pone.0240846.
69. Bianco S, Ciocca G, Marelli D. Evaluating the performance of structure from motion pipelines. J Imaging. 2018;4(98):1–18. https://doi.org/10.3390/jimaging4080098.

70. Zuo Y, et al. A comprehensive review of vision-based 3D reconstruction methods. Sensors. 2024;24(18). https://doi.org/10.3390/s24185861. Article 5861.
71. Guibert I, Hayden R, Sidobre C, Lecellier G, Berteaux-Lecellier. Effect of coral–giant clam artificial reef on coral recruitment: insights for restoration and conservation efforts. Restor Ecol. 2024;32(2):e14145. https://doi.org/10.1111/rec.14145.
72. Fakan EP, Allan BJM, Illing B, Hoey AS, McCormick MI. Habitat complexity and predator odours impact on the stress response and antipredation behaviour in coral reef fish [. PLoS ONE. 2023;18(6):e0286570. https://doi.org/10.1371/journal.pone.0286570.
73. Sustainable Oceans International. 3D printing contributing to underwater conservation. 3D Printing Industry. 2013 Jul 25 [cited 2025 Jul 14]. https://3dprintingindustry.com/news/3d-printing-contributing-to-underwater-conservation-2509
74. Reef Design Lab. 3D printed reefs. Reef Design Lab; 2020 [cited 2025 Jul 14]. https://www.reefdesignlab.com/3d-printed-reefs
75. Liang Z, Smith J, Chen Y, et al. 3D printed artificial coral reefs: design and manufacture. Low Carbon Mater Green Constr. 2024;2:23.
76. Riera R, Pires PR, Cacabelos E, et al. Seasonal variation of food–web structure and stability of a typical artificial reef ecosystem in the Bohai sea, China. Front Mar Sci. 2022;9:830324.
77. Department of Marine and Coastal Resources. Annual Report Fiscal Year 2019. Bangkok, Thailand: Department of Marine and Coastal Resources; 2020.
78. Ahmad SA, Isa MM, Rashid NA. Economic impact of artificial reefs: A case study of small scale fishers in terengganu, Peninsular Malaysia. Fish Res. 2014;151:122–9. https://doi.org/10.1016/j.fishres.2013.10.018.
79. John H. Fears India's huge reef rollout could do more harm than good. Dialogue Earth. 2025 Jan 31 [cited 2025 Jun 14]. https://dialogue.earth/en/ocean/fears-indias-huge-reef-rollout-could-do-more-harm-than-good/
80. AMAC Properties. Dubai Reef Initiative: one of the world's largest purpose-built reefs [Internet]. [place unknown]: DAMAC Properties; [cited 2025 Jul 14]. https://www.damacproperties.com/en/blog/dubai-reef-initiative-or-one-of-the-worlds-largest-purpose-built-reefs-2378/
81. Kheawwongjan A, Kim DS. Present status and prospects of artificial reefs in Thailand. Ocean Coast Manag. 2012;55:20–9. https://doi.org/10.1016/j.ocecoaman.2011.11.001.
82. Norman DA. The design of everyday things. Rev and expanded ed. New York: Basic Books; 2013.
83. Bortone SA, Brandini FP, Fabi G, Otake S. Artificial reefs in fisheries management: a global perspective. Front Mar Sci [Internet]. 2020;7:282. https://doi.org/10.3389/fmars.2020.00282/full
84. Supongpan S et al. Artificial Reefs in Thailand: structure, materials, and deployment depth. Coresea Project Report [Internet]. 2006 Dec [cited 2025 Jul 14]; http://hdl.handle.net/20.500.12067/647
85. Pham LT, Huang JY. 3D printed artificial coral reefs: design and manufacture. Low Carbon Mater Green Constr. 2024;2:23.
86. COREsea. Artificial Reefs. Koh Phangan: COREsea—Conservation and Research; [cited 2025 Jun 15]. https://coresea.com/project/artificial-reefs/
87. Zheng X, Xu Q, Liu Y, Zhang H, Zhang W. Effects of structural characteristics of artificial reefs on fish assemblages: balancing void spaces and surface complexity. Front Mar Sci [Internet]. 2023;10:1130626. https://doi.org/10.3389/fmars.2023.1130626/full
88. Pham LT, Huang JY. 3D printed artificial coral reefs: design and manufacture. Low Carbon Mater Green Constr. 2024;2:23. https://doi.org/10.1007/s44242-024-00056-4. https://link.springer.com/article/.
89. Park JS, Kim DH. Performance evaluation of multi-layered submerged artificial reefs for coastal protection and habitat creation. Ocean Eng. 2013;72:1–13.
90. Paxton AB, Shaver EC, Scholz NL et al. Artificial reefs reveal complexities of ecological structure–function relationships. Ecol Soc. 2022;27(2):10. https://doi.org/10.1002/ecs2.3924
91. Coraggio G, Ceccherelli VU, Bulleri F. Ecological effects of artificial reefs on marine benthic organisms: a review. Oceanogr Mar Biol. 2018;56:289–324.
92. Burt J, Bartholomew A, Usseglio P, Bauman A, Sale PF. Are artificial reefs surrogates of natural habitats for corals and fish in Dubai, UAE? Coral Reefs. 2011;30(3):663–75.
93. Todd PA. Morphological plasticity in scleractinian corals. Biol Rev. 2008;83(3):315–37.
94. Foster SJ, Vincent ACJ. Life history and ecology of seahorses: implications for conservation and management. J Fish Biol. 2004;65(1):1–61.
95. Rouse S, Porter JS, Wilding TA. Artificial reef design affects benthic secondary productivity and provision of functional habitat. Ecol Evol. 2020;10(4):2122–30. https://doi.org/10.1002/ece3.6047.
96. Monchanin C, Mehrotra R, Haskin E, Scott CM, Urgell PP, Allchurch A, Arnold S, Magson K, Hoeksema BW. Contrasting coral community structures between natural and artificial substrates at Koh tao, Gulf of Thailand. Mar Environ Res. 2021;169:105505. https://doi.org/10.1016/j.marenvres.2021.105505.
97. Petersen D, Laterveer M, Schuhmacher H. Spatial and Temporal variation in larval settlement of reef-building corals in mariculture. Mar Ecol Prog Ser. 2005;290:109–19.
98. Golbuu Y, Victor S, Penland L, Idip D, Emaurois C, Okaji K, et al. Palau's coral reefs show differential habitat recovery following the 1998 bleaching event. Coral Reefs. 2007;26(2):319–32.
99. Elmer F. Factors affecting coral recruitment and calcium carbonate accretion rates on central Pacific coral reefs. Wellington: Victoria University of Wellington; 2016.
100. Chaiyong S, Poomlard S. Reclaiming the oceans. Bangkok Post; 2023 Jan 23 [cited 2025 Jul 14]. https://www.bangkokpost.com/life/social-and-lifestyle/2488987/reclaiming-the-oceans
101. Thailand Scuba Diving. Coral restoration in Thailand: methods, projects, and challenges. Thailand Scuba Diving; [cited 2025 Jul 14]. https://thailand-scubadiving.com/coral-restoration/
102. Australian Government Department of Climate Change, Energy, the Environment and Water. Artificial reefs. Canberra: DCCEEW. 2023 [cited 2025 Jul 14]. https://www.dcceew.gov.au/environment/marine/sea-dumping/artificial-reefs

Publisher's note