Artificial reefs through additive manufacturing: a review of their design, purposes and fabrication process for marine restoration and management

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Abstract

Purpose – The purpose of this paper is to review cases of artificial reefs built through additive manufacturing (AM) technologies and analyse their ecological goals, fabrication process, materials, structural design features and implementation location to determine predominant parameters, environmental impacts, advantages, and limitations.

Design/methodology/approach – The review analysed 16 cases of artificial reefs from both temperate and tropical regions. These were categorised based on the AM process used, the mortar material used (crucial for biological applications), the structural design features and the location of implementation. These parameters are assessed to determine how effectively the designs meet the stipulated ecological goals, how AM technologies demonstrate their potential in comparison to conventional methods and the preference locations of these implementations.

Findings – The overview revealed that the dominant artificial reef implementation occurs in the Mediterranean and Atlantic Seas, both accounting for 24%. The remaining cases were in the Australian Sea (20%), the South Asia Sea (12%), the Persian Gulf and the Pacific Ocean, both with 8%, and the Indian Sea with 4% of all the cases studied. It was concluded that fused filament fabrication, binder jetting and material extrusion represent the main AM processes used to build artificial reefs. Cementitious materials, ceramics, polymers and geopolymer formulations were used, incorporating aggregates from mineral residues, biological wastes and pozzolan materials, to reduce environmental impacts, promote the circular economy and be more beneficial for marine ecosystems. The evaluation ranking assessed how well their design and materials align with their ecological goals, demonstrating that five cases were ranked with high effectiveness, ten projects with moderate effectiveness and one case with low effectiveness.

Originality/value – AM represents an innovative method for marine restoration and management. It offers a rapid prototyping technique for design validation and enables the creation of highly complex shapes for habitat diversification while incorporating a diverse range of materials to benefit environmental and marine species' habitats.

Keywords Artificial reefs, Additive manufacturing, Design, Biomimetic, Marine ecosystem restoration

Paper type General review

1. Introduction

As oceans confront unprecedented threats and stressors that damage the entire natural reef ecosystem (Berman *et al.*, 2023), artificial reefs (ARs) have become a key strategy for marine restoration and management. Historically, a variety of objects, ranging from sunken train carriages and discarded tires to modular cement blocks have been deployed to the ocean (Wang *et al.*, 2022). However, recent

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developments in AR manufacturing have shifted towards designs with specific ecological goals and targeted species. Within this context, driven by environmental needs, ecological concerns and technological advances, has particularly highlighted the role of additive manufacturing (AM) to build ARs.

This paper provides a detailed review of how AR manufacturing and deployment have evolved from traditional to modern AM methods. Although the paper provides a broad background on various types of structures, it focuses especially on ARs with biomimetic design features, mimicking natural patterns like those in coral reefs.

AM presents novel opportunities for marine diversity and biomass. Its main benefits include the ability to create intricate structures (Mostafaei *et al.*, 2021) and use innovative materials that support ecological goals and preferred designs while reducing environmental impacts.

1.1 Reef ecosystem

Reef structural complexity plays a crucial role in ecology because of its ability to offer habitats and enhance biodiversity (Yanovski *et al.*, 2017). This complexity refers to the reefs' physical three-dimensional (3D) structure (Graham and Nash, 2013). Such structural complexity in ecosystems foster a range of microhabitats (Figure 1) increasing the diversity and population of related organisms (Crowder and Cooper, 1982).

Reef structures may have substrates that are geogenic (rocky from stone) or biogenic (derived from the carbonate deposition of habitat-forming organisms like trees, oysters, wetland grasses and corals (Jackson-Bué *et al.*, 2022; Richardson *et al.*, 2017)). These substrates host large communities of sessile species, which remain attached to a substratum, and mobile-reef species seeking shelter within the reef environment (Bué *et al.*, 2020).

Coral reefs, significantly impacted by climate change, are renowned for their ability to form diverse structural shapes. This ability often linked to competitive survival and vulnerability to disturbances (Madin *et al.*, 2014), makes then a reference for developing underwater structures. Understanding their shape's adaptation to meet functional needs influenced by local environmental and biological factors (Connell *et al.*, 2004) may be useful to design ARs.

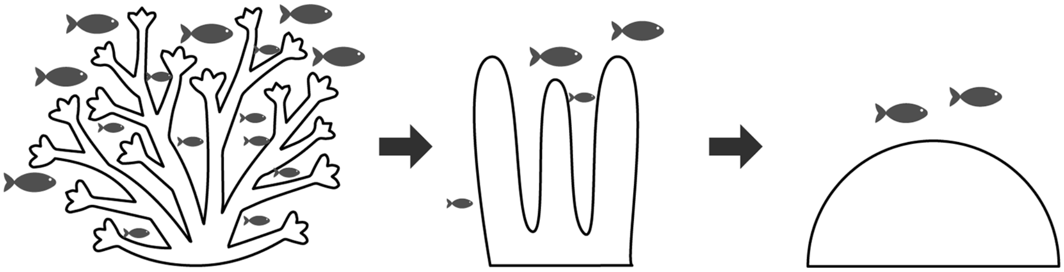
Five common feature configurations have been identified (Figure 2). Although all configurations have the same growth potential, their different shapes allow them to occupy more space, reach greater heights and provide wider areas of shade (Cresswell *et al.*, 2020).

The literature identifies two zones of reef ecosystems, characterised by spatial distribution, water temperature and depth. These are classified in this research as tropical and temperate regions (Ebeling and Hixon, 1991; Stuart-Smith *et al.*, 2022).

In tropical regions, most biogenic reefs consist of Scleractinia coral calcification (Miller, 1995). These corals thrive in shallow areas (up to 30 m) where sunlight facilitates their photosynthesis (Li and Asner, 2023). Beyond their biological role, coral reefs act as barriers against shoreline erosion and provide various ecological services (Hoegh-Guldberg *et al.*, 2017), such as tourism, commercial fishing, scientific research and management activities. All those activities contribute significantly to the economy of that region (Economics, 2013).

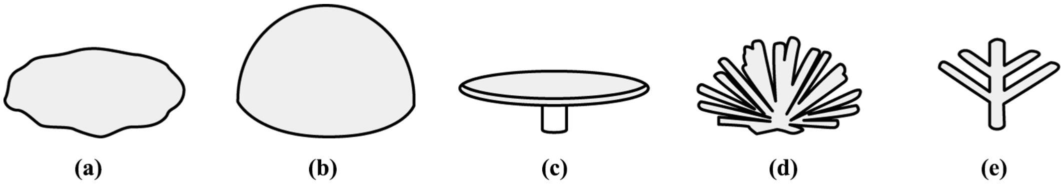
In temperate regions, cold-water coral species are known to form reefs in deeper zones (between 30 and 900 m). Advanced offshore technology has unveiled the true extent of Europe's hidden coral reef ecosystems (Freiwald, 2003). These habitats primarily comprise macro-algae forests, light-dependent Scleractinia corals and non-photosynthetic organisms such as azooxanthellate gorgonians, Antipatharia and sponges (Kahng and Kelley, 2007).

Figure 1 The diagram illustrates the impact resulting from the loss of structural complexity in marine habitats on the ecosystem, leading to the decline of organisms that shelter on them



Source: Figure courtesy and adapted from Fontoura *et al*. (2020)

Figure 2 Most common morphologies of *Scleractinia* corals (biogenic reef-forming) classification



Notes: (a) Encrusting; (b) hemispherical; (c) tabular; (d) corymbose; (e) branching
Sources: Adapted from (Cresswell *et al*., 2020); figure by authors

Unfortunately, ocean warming and acidification pose significant threats to coral reef growth, particularly in tropical regions, resulting in high mortality rates during massive bleaching events every year (Selwood *et al.*, 2015). The calcium carbonate of coral structure is highly sensitive to these anthropogenic factors (Cornwall *et al.*, 2021). Studies indicate that while initial disturbances may not immediately impact the reef structure, a loss or erosion of structural complexity can drastically affect associated organisms, such as fish communities, leading to severe consequences (Sano *et al.*, 1987; Graham and Nash, 2013).

1.2 Artificial reefs

ARs are defined as submerged structures intentionally placed on the seabed to protect, regenerate and/or enhance populations of living marine resources (Cardenas Rojas *et al.*, 2021). The definition is outlined in various assessments, including those by the Guidelines for the Placement at Sea of Matter for a Purpose other than the Mere Disposal (UNEP-MAP, 2005), the Guidelines for the Placement of Artificial Reefs (London Convention and Protocol/UNEP, 2009), the Assessment of construction or placement of ARs (OSPAR, 2009) and the Guidelines and management practices for artificial reef siting, use, construction and anchoring in Southeast Florida (Lindberg and Seaman, 2011), becoming a significant technique for resource enhancement (Bohnsack and Sutherland, 1985). ARs are considered human engineering interventions aimed at restoring and improving damage habitats, increasing fishery resource efficiency, managing aquatic resources and promoting underwater tourism (Spagnolo *et al.*, 2015). The deployment of ARs may serve multiple purposes: protecting sensitive habitats from fishing industry activities; restoring degraded habitats; mitigating habitat loss; enhancing biodiversity; offering shelter to marine populations; providing new substrates for benthic communities; boosting professional and recreational fisheries and diving areas; managing coastal activities; fostering research and education; and forming networks of marine protected areas (MPAs) (Spagnolo *et al.*, 2015).

1.2.1 Trends in the evolution of manufacturing artificial reefs

Over the years, a diverse array of construction methods, materials and morphologies has emerged (Fauzi *et al.*, 2017). Selecting the right materials is crucial for achieving the desired outcomes as it influences the design and durability of the ARs, colonisation by marine organisms and consequently the fish populations residing in these structures (Spagnolo *et al.*, 2015).

The materials used for building ARs were classified in two groups:

1. Natural raw materials. Unprocessed substances obtained from natural environment (Marschallek and Jacobsen, 2020). Common materials for ARs include quarry rocks (Palmer-Zwahlen and Aseltine, 1994), rocky conglomerates (Baine, 2001; Feary *et al.*, 2011), bivalve shells (Fabi *et al.*, 2011), wood (Alam *et al.*, 2020) and organic residues like banana particles waste (Mat Jusoh *et al.*, 2018).
2. Composite materials. These are produced by combining two or more substances with varying properties, such as cement (Baine, 2001; Dennis *et al.*, 2018), metal (Mercader *et al.*, 2017; Scarcella *et al.*, 2015), polymers (Omar, 1995), ceramics (Kalam *et al.*, 2018) and fibreglass (Kheawwongjan and Kim, 2012). Cement is notably preferred for its suitability and cost-effectiveness in AR manufacturing, facilitating the creation of specific designs (Spagnolo *et al.*, 2015) through casting moulds or AM.

Concerning the design typology used for ARs, a range of shapes, from randomly placed objects to purposefully designed structures, have been implemented over the years (Bohnsack and Sutherland, 1985). Three design typology classification have been identified:

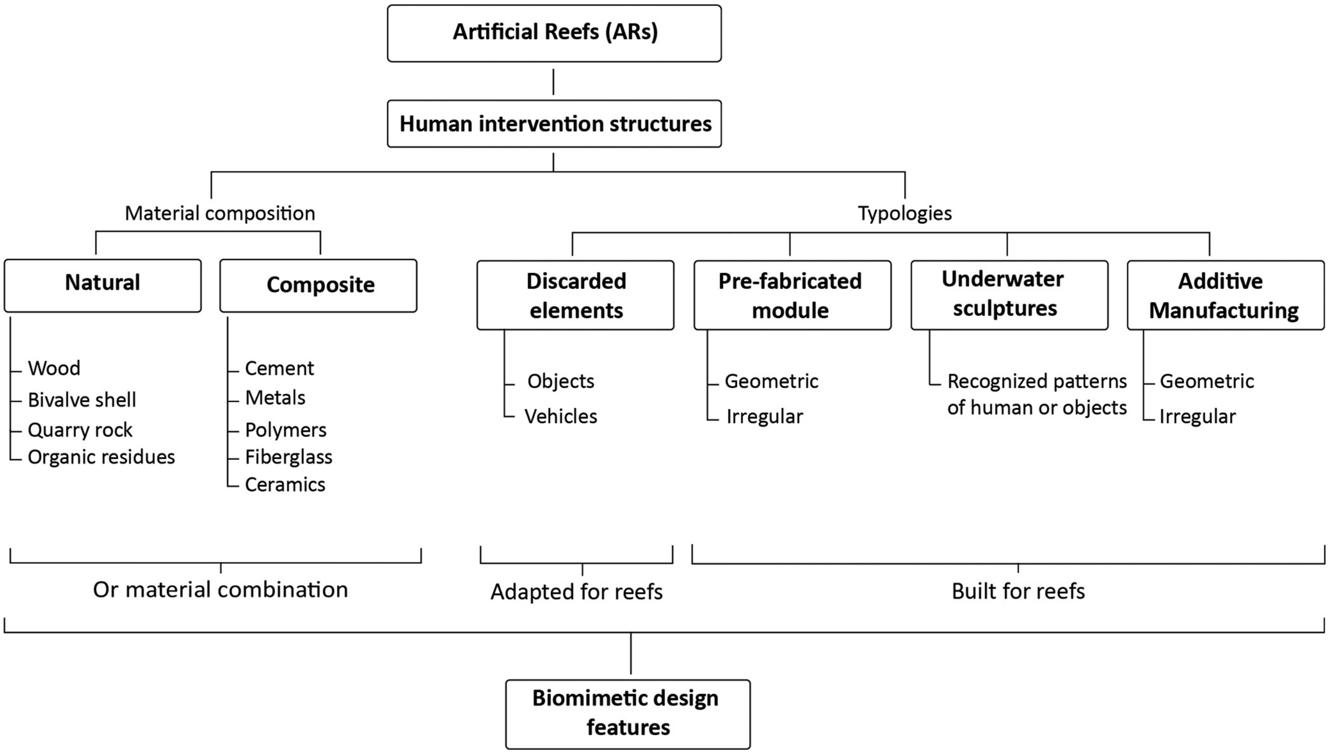
1. Underwater sculptures. Structures with artistic and narrative significance, often created by well-known artists. Designed to enhance marine biodiversity, support citizen science and foster education (Smith *et al.*, 2021). Their primary aim is to attract subaquatic tourism, offering underwater museum experiences, accessible through scuba diving or snorkelling. Notable examples include the Museum of Underwater Art (Smith *et al.*, 2021), the Museum of Art (Bujniewicz, 2019), and the Neptune Memorial Reef (Neptune Memorial, 2007).
2. Unit shape. Structures with geometric or abstract morphology are developed individually or as assemblies of multiple units. While capable of functioning independently, they are typically grouped together as modular components. This design approach primarily facilitates manufacturing via mould casting or AM. Common shapes include cubes, pyramids, triangular prisms and various organic forms (Yaakob *et al.*, 2016).
3. Discarded elements. Objects originally intended for other uses, which were dropped offshore at the end of their life cycle or after discontinuation of their production, have been adapted as ARs. Examples include shipwrecks (Santos *et al.*, 2010), car tires (Sherman and Spieler, 2006), war tanks/armed force vehicles (Sheehy *et al.*, 2020) and subway cars (Galiano, 2003), among others. Accidentally sunken elements also fall into this category. The primary advantage of anchoring these structures to the seabed is the elimination of their fabrication needs while inadvertently promoting a non-targeted biodiversity. However, they typically do not support microstructural habitat development, may contain corrosive materials to certain species, lack potential for enhancing marine abundance and are introduced into environments where they do not naturally exist.

Depending on the selected materials and shape, ARs can either emulate patterns found in the marine environment or stand as completely foreign elements within it. Biomimetics involves structural transformation, drawing from nature's sustainable and resilient designs and solutions (Chen *et al.*, 2015). ARs built with biomimetic-based features enhance the local environment's benefits (Vivier *et al.*, 2021). This paper concerned with AR characteristics like structural complexity, surface rugosity and morphology. Structures incorporating design features from natural reefs are specially effective in increasing and sustaining biodiversity (Dafforn *et al.*, 2015; Loke *et al.*, 2015; Tokeshi and Arakaki, 2012; Torres-Pulliza *et al.*, 2020).

The key aspects discussed in this section are presented in the concept map illustrated in Figure 3.

Over time, the emphasis on using sustainable materials and integrating artificial structures into the natural environment has become a key trend in the development of ARs (Figure 4). Technological advancements have facilitated the use of innovative tools and methods for their fabrication. Notably, the trend towards designing structures with parametric shapes, which allow

Figure 3 Concept map of AR manufacturing classifications according to the material and typology used



Source: Figure by authors

dimensions to change shape and geometry, represents a significant future direction in AR manufacturing (Levy *et al.*, 2022).

1.2.2 Effectiveness of artificial reefs

The efficiency of ARs depends on several critical factors highlighted in various studies. These factors include the importance of design management and reef complexity (Baine, 2001), targeting species and habitats for cost-effective ARs (Gibson Banks *et al.*, 2021) and understanding the hydrodynamic, morphological and ecological behaviour of ARs (Cardenas Rojas *et al.*, 2021). Performance criteria for developing these structures should include detailed information of the target species like population abundance, size structure and the reef-dependent biota; and detailed information of the habitat, such as larval recruitment, immigration, growth, reproduction, mortality and emigration (Carr and Hixon, 1997). A deep understanding or targeted species and recruitment mechanisms is essential for predicting colonisation rates in ARs.

To ensure the effective implementation of ARs, a comprehensive guideline has been compiled (Figure 5) outlining necessary considerations (Baine, 2001; Jahan and Strezov, 2019; Matus, 2020; Vivier *et al.*, 2021). These parameters are divided into seven categories: planning and management, design features, material compositions, habitat conditions, structural stability, environmental variables and monitoring techniques.

A novel approach to marine reef restoration uses AM to support natural reef-building processes, serving educational and scientific development purposes. While this technology cannot eliminate anthropogenic influences or the coral bleaching phenomenon impacting coral reefs globally, it offers innovative solutions for sheltering species and fostering the settlement of benthic organisms reliant on reefs for survival.

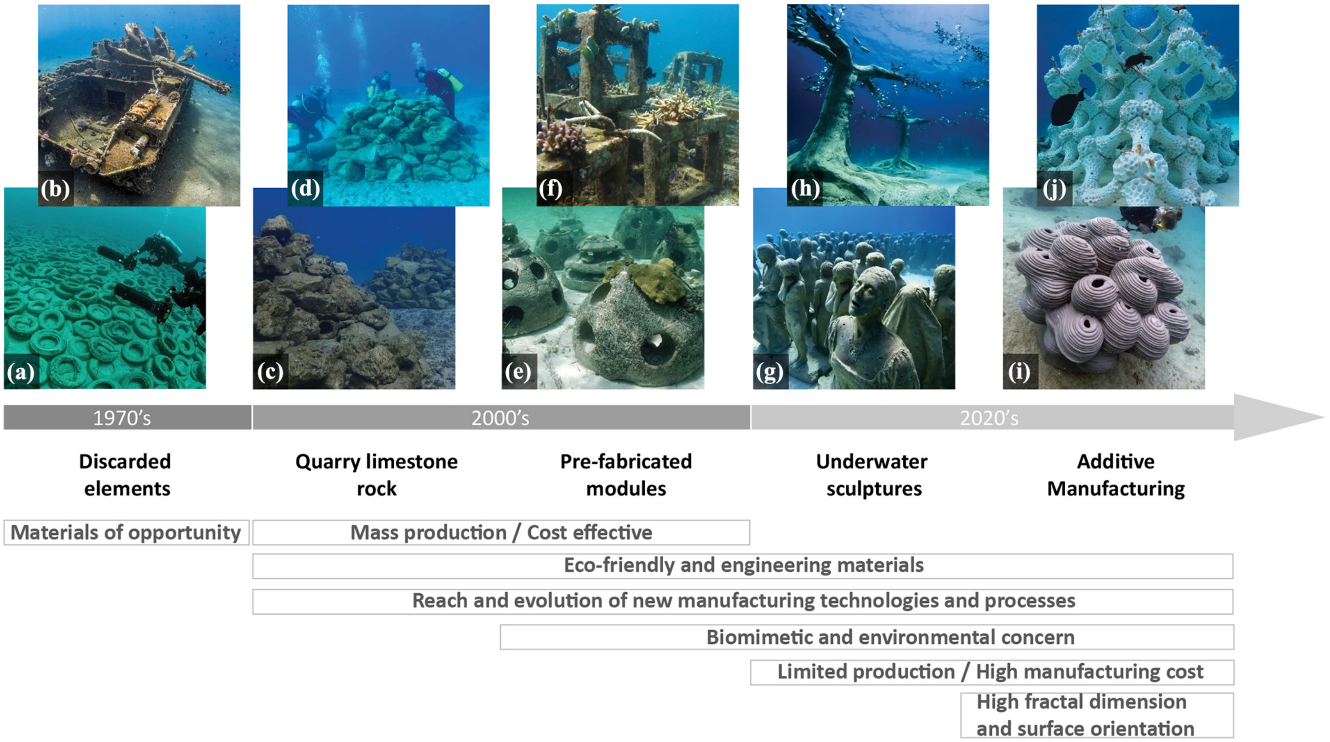
1.3 Additive manufacturing technologies

AM has become an important technology integrating machinery, computer numerical control and a variety of materials including polymers, metals, ceramics, cementitious and composite materials in the global manufacturing field (Shi *et al.*, 2021). AM offers mass customisation, prototype production and competitive advantages depending on the application, such as lighter products, multi-material capability, ergonomic design, efficient production times, fewer assembly errors and reduced costs along with a combination of more sustainable manufacturing processes (Jiménez *et al.*, 2019).

This innovative technology uses an additive approach to build complex shapes layer by layer (Pereira *et al.*, 2019). The 3D models are created using 3D computer-aided design (CAD) software or obtained via reverse engineering tools like 3D scanners (Zhang and Liou, 2021). Expanding across various industrial sectors, AM enhances functionality, productivity and competitiveness, revolutionising numerous production methods (Vafadar *et al.*, 2021; Lim *et al.*, 2016). Unlike conventional subtractive manufacturing and formative manufacturing, which involve casting into moulds or removing material through machining, AM offers industry benefits in customisation, complexity (Pereira *et al.*, 2019), reduced waste, and improved sustainability (Pilz *et al.*, 2020; Rouf *et al.*, 2022).

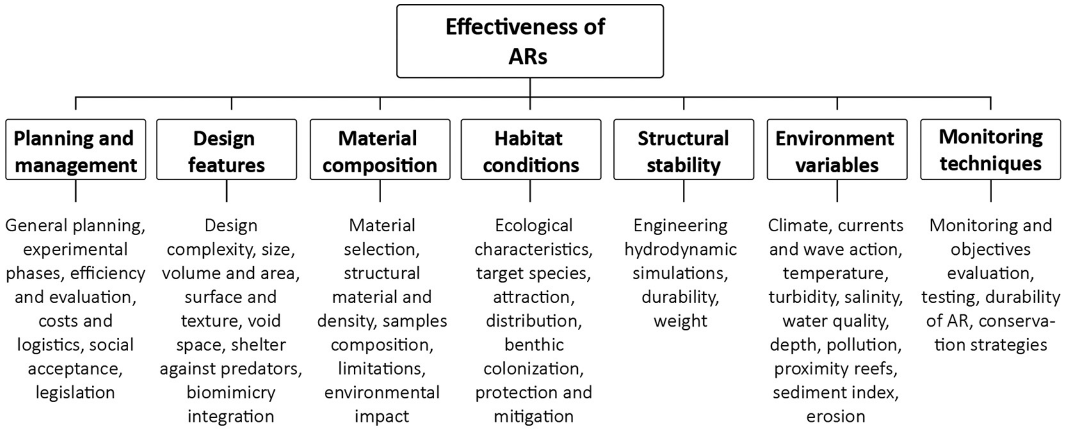
While conventional processes can produce complex geometries, they often demand significant process planning,

Figure 4 Evolution map of AR manufacturing trends over the years



Notes: (a) Broward ARs built from old car tires, Florida 1972; image credit Mikkel Pitzner; (b) military tank sunk to create an artificial coral reef, Aqaba 1980; image credit Shahar Shabtai; (c) and (d) ARs made from locally limestone rock source, Bay of Ranobe 2016 (ReefDoctor, 2016); (e) Reef Ball AR deployment, made from cement (Krumholz and Barber, 2011); (f) 500 cement units placed in the Gulf of Thailand, 2017 Charoen Pokphand Group; (g) silent evolution underwater sculpture (deCaires, 2012); (h) MUSAN Ayia Napa underwater sculpture (deCaires, 2021); (i) InnovaReef (Chulalongkorn, 2020); (j) MARS (Goad, 2018)
Sources: Levy *et al.* (2022); Reef Ball (1995); figure by authors

Figure 5 Concept map of general considerations to ensure the effectiveness of manufactured ARs



Sources: Figure courtesy of Baine, (2001); Jahan and Strezov (2019); and Vivier *et al*. (2021)

assembly steps and post-processing efforts to achieve the desired final product geometry.

AM applications in marine ecosystems hold vast potential for future research and development, playing a key role in the manufacture of ARs compared with conventional industrial processes. There are several reasons why traditional methods might be considered less effective than AM processes:

- *Limited customisation*. Traditional manufacturing processes often provide restricted flexibility in creating customised design features for specific ecological goals or targeted species. In contrast, AM technologies facilitate the production of ARs with variations in shape, texture or size. This versatility can be tailored to various purposes, deployment areas or the scalability of AR implementation. Unlike conventional methods, which require different moulds for material casting (thus increasing production costs) or use subtractive methods to sculpt the desired shape (leasing to considerable waste), AM offers a more efficient and adaptable solution.
- *Material limitations*. Traditional manufacturing may face limitations in using materials that enhance durability and ecological compatibility. In contrast, AM technologies allow for experimentation with new material combinations, reducing environmental impact and benefiting marine species.
- *Complex morphologies*. ARs intended to support specific marine life and mimic natural reefs often require complex shapes. Traditional methods may have difficulties to produce intricate designs, internal cavities and specific reliefs needed for these purposes.
- Resource efficiency. AM technologies often provide greater resource efficiency by minimising material waste during the production process. Conventional methods might be less precise and generate more waste, raising environmental concerns.
- *Time and cost*. The speed and cost-effectiveness of manufacturing methods can vary based on the urgency of marine conservation goals. AM offers faster prototyping and production capabilities. However, for large-scale production, traditional processes might be more advantageous and faster due to the moulding techniques.
- *Adaptability*. As the marine environment is dynamic, ARs need to be adaptable to changing conditions. Traditional manufacturing may restrict the adaptability of structures, while AM allows rapid modifications and enhancements in a short time frame.

In summary, the limitations of traditional manufacturing in terms of customisation, material selection, shape complexity, resource efficiency, speed and adaptability make it less effective to meet the requirements of building ARs and to address their ecological and conservation goals.

Experimental studies have highlighted how AM technologies bring innovative methods and materials to this field. 3D bioprinting (Wangpraseurt *et al.*, 2020) has shown the potential for cultivating microalgae with high cell density. In addition, hybrid photosynthetic materials have been synthesised to replicate the morphological, optical and mechanical characteristics of living coral tissue and skeletons.

Coral propagation substrates (Matus *et al.*, 2021) developed using AM and silicone moulds to convert 3D models into limestone and Portland cement substrates have helped assess the impact of textured surfaces, complex morphology and chemical composition on coral propagation and growth.

Sensory materials for AM (Gutiérrez-Heredia *et al.*, 2016) react to environmental changes like temperature, ultraviolet (UV) light and pH, serving as indicators for changes in water, temperature, salinity or pollution. These materials have significance for AR applications.

Coral skeletons (Albalawi *et al.*, 2021) have used AM to create artificial coral skeletons using calcium carbonate photo-initiated ink, enhancing the growth rate of live coral fragments and streamlining the reef transplantation process while also reducing costs.

Finally, 3D tiles (Levy *et al.*, 2023) were manufactured with ceramic terracotta clay through material extrusion to mimic natural reef topographies, acting as valuable tools for monitoring coral reef reformation.

AM technology processes are classified by ISO/ASTM 52900 standard, which further subdivides them based on the type of material used: solid, powder, or liquid-based (Alghamdi *et al.*, 2021). The AM processes are identified using the following nomenclature: binder jetting (BJ); direct energy deposition (laser engineered net shaping, electron beam melting); material extrusion (ME) (fused filament fabrication – FFF, paste deposition modelling – PDM); material jetting (polyjet, multijet and nanoparticle jetting); powder bed fusion (selective laser sintering, selective laser melting, direct metal laser sintering, selective heat sintering); sheet lamination (ultrasonic consolidation, laminated object manufacturing); and vat photopolymerisation (stereolithography; digital light processing; liquid crystal display; continuous liquid interface production and two-photon polymerisation).

In this paper, the most common techniques for AR manufacturing are highlighted in blue colour in Figure 6.

1.3.1 Binder jetting process

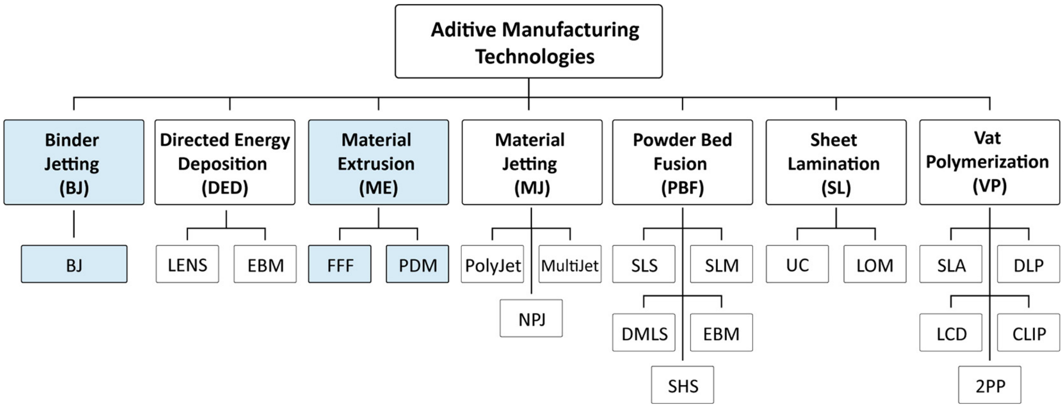
This process is an inkjet-based method used to create 3D shapes (Sachs *et al.*, 1993). It involves spreading powdered material into a layer and selectively binding it into the desired shape with a binder, typically a polymeric liquid (Mostafaei *et al.*, 2021). This technique enables the relatively low-cost production of complex geometries without thermal distortion, as it operates at room temperature (Leary, 2020, p. 13).

Figure 7 illustrates the process where thin layers of powder are spread, and the printhead selectively ejects and deposits the binder droplets into the power bed, building the final geometry layer by layer (Mostafaei *et al.*, 2017, 2021). An integrated computer numerical control (CNC) system provides three-axis movement. The *Z*-axis allows the bed platform to move up and down, whereas the *X*- and *Y*-axis enable the printhead to move and draw the layer shape using the binder as ink (Caldeira, 2021).

Compared with other AM processes, BJ allows notable scalability (Zocca *et al.*, 2017), uses a diverse range of materials (Chen *et al.*, 2022a; Mostafaei *et al.*, 2021), eliminates the need for support structures for overhanging features (Rouf *et al.*, 2022), allows full recyclability of unprinted powders (Gibson *et al.*, 2021a) and processes the largest build volume (up to 2,200 × 1,200 × 600 mm) among all AM techniques (Mostafaei *et al.*, 2021).

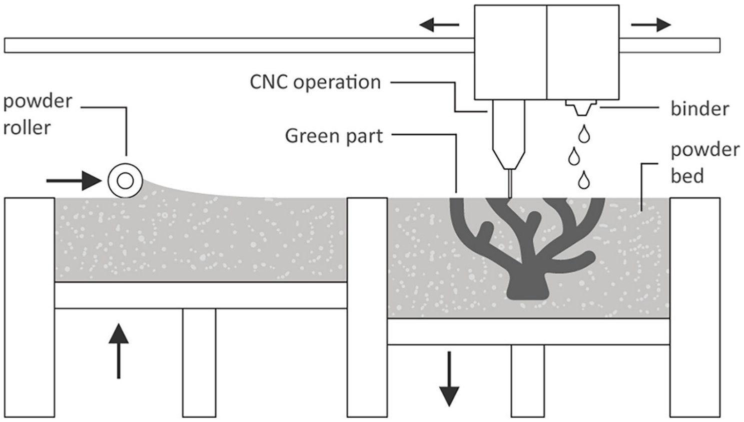
The BJ process uses a wide range of materials (Figure 8) such as ceramics, metals, polymers, composites, glass, wood, composites (Shrestha and Manogharan, 2017) and sandstone (Hodder and Nychka, 2019). The binder is crucial for filling the interstitial spaces between powder layers (Mostafaei *et al.*, 2021). Various binders are used according to the material used, including water-based binders like maltodextrin (Suwanprateeb and Chumnanklang, 2006), sucrose (Sachs *et al.*, 1993) and

Figure 6 Concept map of AM process categories based on ISO/ASTM 52900



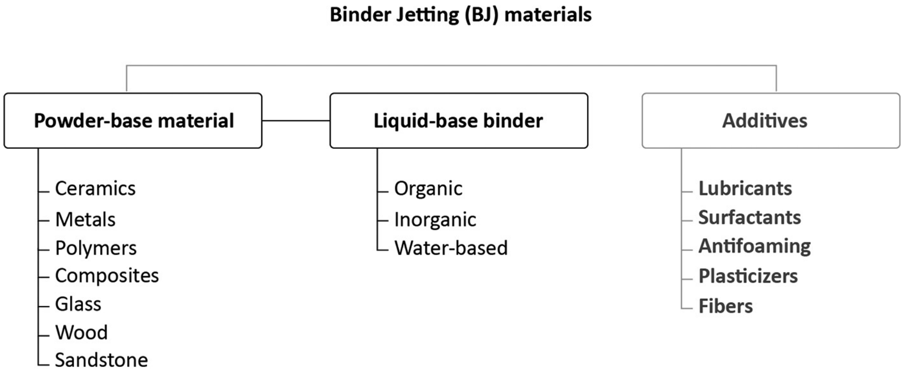
Note: Processes highlighted in blue colour are used for AR manufacturing
Source: Figure courtesy of Garcia-Cardosa *et al*. (2022)

Figure 7 Binder jetting additive manufacturing scheme of the operation machinery process



Source: Figure courtesy and adapted from 3DEO, 2018

Figure 8 Concept map illustrates the category of materials used in binder jetting process, including powders, liquids and additives



Source: Figure by authors

sodium silicate; and versatile organic liquids such as butyral resins (Sachs *et al.*, 1993), polymeric resins (Utela *et al.*, 2008), various polyvinyl (Feenstra, 2005) and preceramic polymers like polycarbosilane (Sachs *et al.*, 1993), polysiloxanes (Greil, 2000) and aluminium amides (Peuckert *et al.*, 1990).

Additives, highlighted in grey in Figure 8, can be optionally used to improve the performance of the powder deposit ability, printing behaviour, mechanical properties and post-processing (Utela *et al.*, 2008). Fibre additions, such as polymeric, ceramic, graphite and fiberglass, may also be incorporated to reinforce the powder material (Bredt *et al.*, 2002).

The impact of binder material on the marine environment varies depending on the additives used. The binder provides essential cohesion for the printed layers and is vital for the structural integrity of the printed part. It is not feasible to exclude this component from the mixture. Common binders like polymers and resins may harm marine life, but recent studies have developed bio-friendly binders (Ahn *et al.*, 2021; Boukhelf *et al.*, 2022; Salari *et al.*, 2022) aimed at reducing environmental impact in marine applications such as ARs. BJ has been used to build ARs using marine-safe materials such as cement, mineral composites, sand or clays (Boskalis, 2017).

This process shows high potential in AR development, with significant scalability, the ability to build large volumes, use sustainable materials and create a rough surface finish that provides more area for organisms to colonise. However, the fabrication of large structures presents challenges such as the need for heavy machinery, logistical issues and high transportation costs to the deployment site.

1.3.2 Material extrusion process

It is a process that involves extruding material and depositing it layer by layer, facilitated by the relative movement between the nozzle and the print bed. During extrusion, the semi-solid material solidifies upon reaching its final position and shape (Gibson *et al.*, 2021b; Oleff *et al.*, 2021). Various sub-categories are defined by the type of extruder, as illustrated in Figure 9(a): plunger, gear or screw; the feedstock form: filaments, paste or pellets; and the kinematic design represented in Figure 9(b): cartesian, delta, polar or robot arm (Kampker *et al.*, 2019).

FFF is a widely used AM process (Rashid and Koç, 2021) that works by heating the nozzle and extruding a filament of various thermoplastic materials (Sola, 2022). This technology enables rapid prototyping of experimental samples for design validation and cost-effective manufacturing. It includes small-scale desktop 3D printers (with a build volume of up to $300 \times 300 \times 300$ mm^3) and larger 3D printers up to $1{,}005 \times 1{,}005 \times 1{,}005$ mm^3. However, most consumables are limited to polymer materials, which are not ideal for ARs because of their negative environmental impact, reduced durability in seawater conditions and limited scalability for producing large structures.

ME also encompasses PDM, the denomination used in this paper due to the lack of clarity in the literature regarding the appropriate terminology for this technique. In PDM, paste material is extruded and deposited at room temperature, solidifying through the evaporation of water or other solvents (Ruscitti *et al.*, 2020). The principal AM process stages include mixing, pumping and extruding (Zhong and Zhang, 2022).

The extrudability factor is critical in this process as the mixtures must resist gravity to ensure consistent extrusion throughout the printing period. Any interruptions or head repositioning may affect the extrusion flow rate, geometry, density and other properties (Perrot *et al.*, 2018).

This technique enables the creation of large volumes for ARs and the use of a broad range of sustainable materials (Bhattacherjee *et al.*, 2021). For mortar development, PDM primarily uses three types of materials illustrated in Figure 10: ceramics (Romanczuk-Ruszuk *et al.*, 2023), cementitious (Buswell *et al.*, 2018) and geopolymers (Zhong and Zhang, 2022).

For cementitious-based materials, ordinary Portland cement (OPC) is typically used (Albar *et al.*, 2020), combined with supplementary aggregates of natural or artificial origin. These aggregates include pozzolanic materials like fly ash, silica fume, metakaolin and blast-furnace slag; sandstone; recycled rubble from construction and demolition waste such as brick (Christen *et al.*, 2022); glass waste (Ting *et al.*, 2021); and biological residues like seashells. In addition, mixtures are used to alter density or viscosity, enhance flowability, reduce water content, strengthen the mixture or generally improve the printability and rheological properties. These mixtures includes superplasticizers, viscosity modifiers, accelerators or retarders (Ahmed, 2023; Robayo-Salazar *et al.*, 2023).

Ceramic-based materials are classified into five categories (Table 1): oxides, non-oxides, mixed oxides, bio-ceramics and clays (Romanczuk-Ruszuk *et al.*, 2023). The mixture typically includes solids, water and additives such as polymer plasticizers or inorganic electrolytes to control particle dispersion and viscosity (Ben-Arfa and Pullar, 2020; Lamnini *et al.*, 2022). The ceramic paste should possess a high concentration of ceramic powder and enough plasticity to be extruded (He *et al.*, 2021) and subsequently sintered at high temperatures for solidification (He *et al.*, 2021).

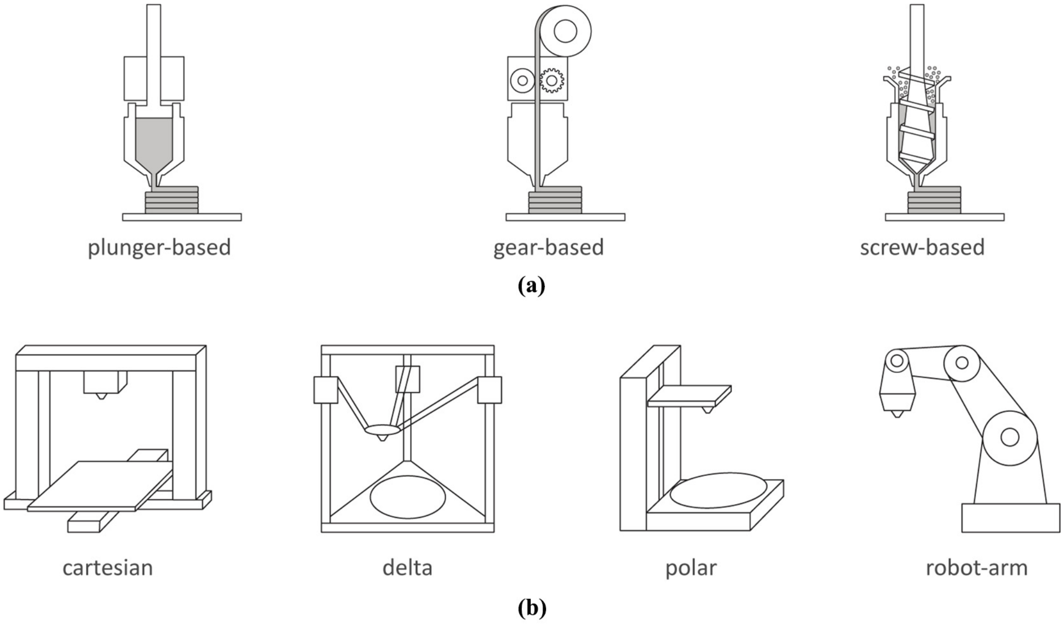
For geopolymers-based materials, the mixture must be thixotropic, meaning its viscosity decreases under mechanical stress, a crucial characteristic for this AM process. Geopolymers offer benefits like high strength, resistance to high temperatures, corrosion and permeability (Panda *et al.*, 2019). Their ability to incorporate waste materials and reduce CO_2 emissions makes them a promising "green" alternative to OPC (Lazorenko and Kasprzhitskii, 2022). Geopolymers are a type of inorganic material with a 3D framework, formed through the alkaline-silicate activation of aluminosilicate precursors at room or elevated temperatures (Ren *et al.*, 2021). Recent studies have explored the use of geopolymers as binders in the extrusion of cementitious-based materials (Chen *et al.*, 2022b; Şahin and Mardani-Aghabaglou, 2022).

The composition of the AM mixture may include aluminosilicate activating agents, plasticizers, accelerators, hardening retarders and aggregates like silica (quartz), tailored to the required properties (Lazorenko and Kasprzhitskii, 2022). Including fine and medium-sized sand particles in the mixture can enhance its extrudability (Bong *et al.*, 2021).

1.3.3 Advantages and limitations of additive manufacturing processes to build artificial reefs

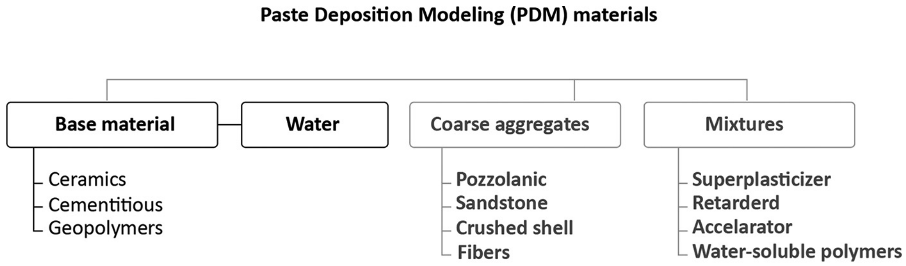
BJ and ME are the primary processes in AR manufacturing as they use favourable and diverse materials for marine habitats and benthic ecosystems, such as non-toxic substances with inert pH (Berman *et al.*, 2023). These processes also facilitate the implementation of innovative mortar formulations, enable the

Figure 9 The diagram classifies the material extrusion process according to (a) three extruder mechanisms and (b) four kinematic designs for material deposition



Notes: (a) Extruder type; (b) kinematic design
Source: Figure courtesy and adapted from Alafaghani *et al.* (2017) and Spoerk *et al* (2019)

Figure 10 Concept map categorizes the materials used in the paste deposition modelling process, into base material, coarse aggregates and mixtures



Source: Figure by authors

Table 1 Classification of ceramic-type materials used in paste deposition modelling process

Material group	Material
Oxides	Aluminium oxide, titanium oxide, zirconium oxide
Mixed oxides	Lead Zirconate titanate, barium titanate
Non-oxides	Zirconium diboride, silicon carbide
Bio-ceramics	Calcium phosphate, hydroxyapatite
Clays	Kaoline

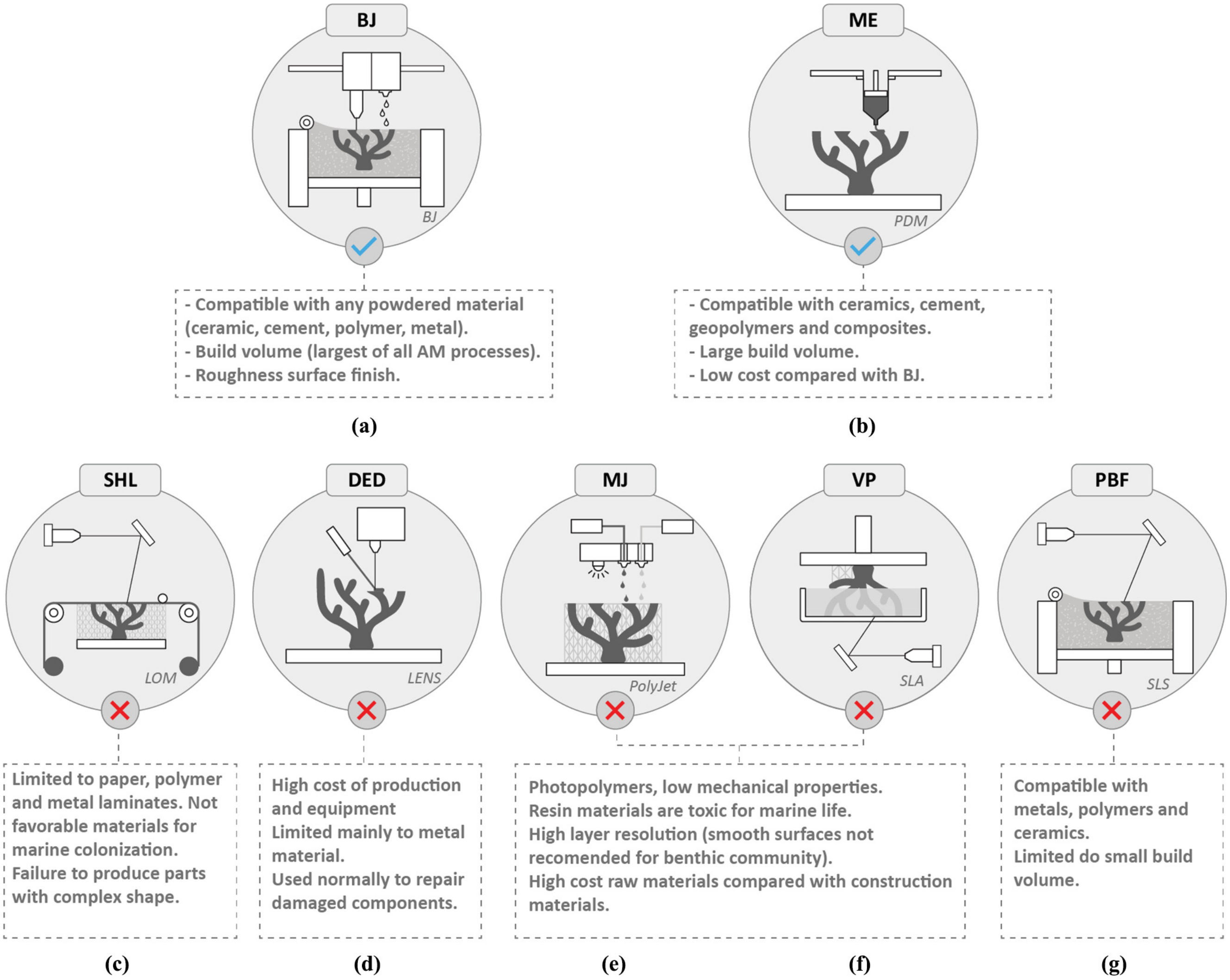
Source: Table courtesy and adapted from Romanczuk-Ruszuk *et al.* (2023)

creation of complex geometries and allow the construction of large and dense structures to ensure stability on the seabed. In addition, they offer benefits of low production costs and require less equipment and labour operation compared with other methods.

Figure 11 illustrates the main advantages and limitations of AM processes to build ARs. BJ and ME have been favoured for their suitability with the material properties required for deposition (Berman *et al.*, 2023) and their capability to create structures with large volume, rugosities and cavities, crucial features for supporting reef life (Torres-Pulliza *et al.*, 2020). Various AR studies have used BJ processes (Erioli and Zomparelli, 2012; Gardiner, 2011; Reef Arabia, 2012). The ME process, particularly PDM, offers a range of extruded materials for AR manufacturing, including cementitious (Dunn *et al.*, 2019; Ly *et al.*, 2021; Yoris-Nobile *et al.*, 2023) and clay ceramic materials (Lange *et al.*, 2020; Levy *et al.*, 2022) materials.

Other AM processes appear unsuitable for AR manufacturing, particularly those using metal materials, which are not considered ideal for ecological solutions (Shah, 2021). The equipment and production costs of manufacturing large volumes with metal are high (Martin *et al.*, 2022), making the process less cost-effective compared with subtractive methods. Heavy metals cannot be degraded by chemical or biological processes and when accumulate in sediments, may cause

Figure 11 The diagram illustrates the advantages of the two AM processes most used for the fabrication of ARs, highlighted in blue, and the main limitations of the other five processes highlighted in red



Notes: (a) BJ = binder jetting; (b) ME = material extrusion; (c) SHL = sheet lamination; (d) DED = directed energy deposition; (e) MJ = material jetting; (f) VP = vat polymerization; (g) PBF = powder bed fusion
Source: Figure by authors

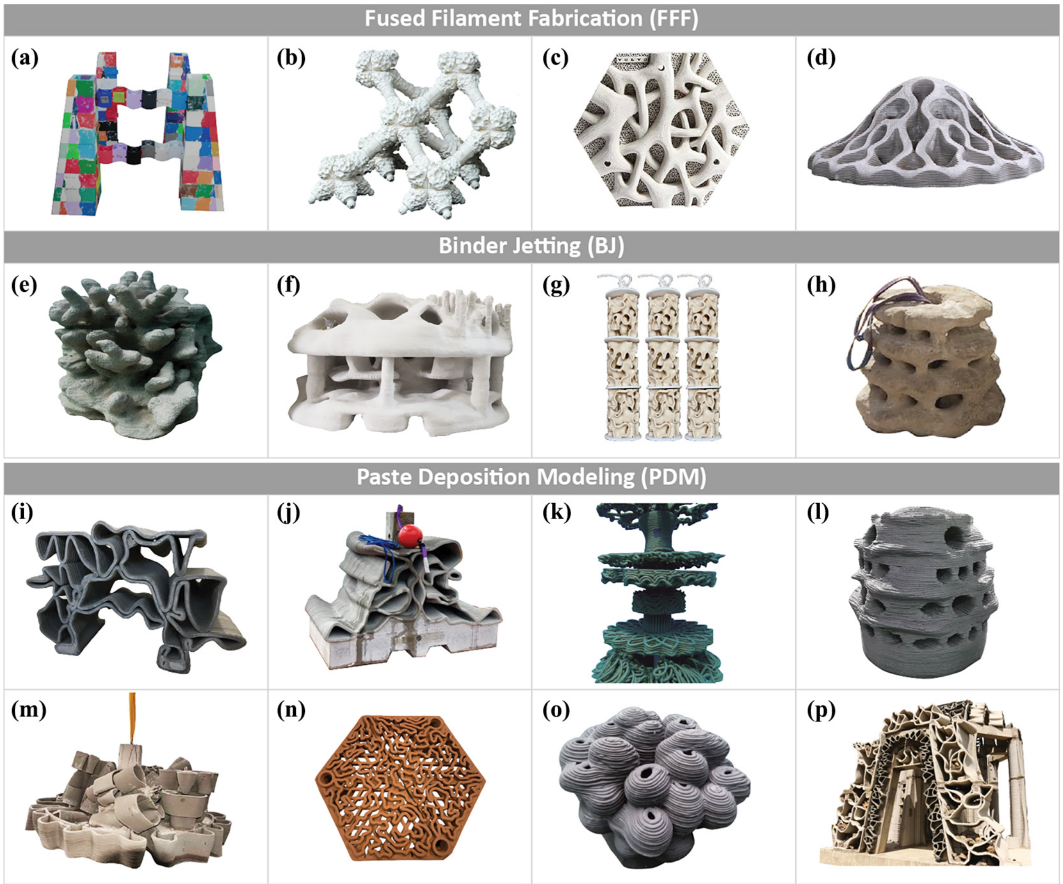
toxicity in various marine organisms (Pan and Wang, 2012). In addition, factors like oxygen, temperature, salinity, pH and water flow can cause corrosion, affecting the longevity of metal structures (Nassar, 2022). However, some ARs do use small metal components as auxiliary materials for structural reinforcement or assembly needs (Goad, 2018; Yoris-Nobile *et al.*, 2023). Given these considerations, processes primarily using metal-based materials, such as sheet lamination and directed energy deposition, have not been considered for AR manufacturing.

Conversely, polymers are well-known to accumulate in sediments, forming microplastics that adversely affect ingestion and egestion processes in marine biota (Huang *et al.*, 2021; Pantos, 2022). This leads to the potential degradation and consequent production of marine debris, contributing to environmental pollution (Boström-Einarsson *et al.*, 2020). Photopolymers like UV resins, often used in processes such as material jetting (MJ) and vat polymerisation, tend to be fragile and biologically incompatible (Li *et al.*, 2023). Although the MJ process can produce high-quality parts with smooth finishes and multi-material/colour options (Gülcan *et al.*, 2021), there are non-essential characteristics for AR manufacturing. Furthermore, the equipment and raw material costs for MJ are high, and its build volume, ranging from 380 × 250 × 200 mm^3 to 1,000 × 800 × 500 mm^3 (3D Systems, 2017), is smaller compared with BJ and ME.

2. Methods

The review, presented in Figure 12, analysed 16 ARs from temperate and tropical regions. These were compiled from 27 scientific papers from the Web of Science and Google Scholar,

Figure 12 Artificial reefs manufactured through AM technologies and categorized by the process used



Notes: (a) Hope 3D (The San Pedro Sun, 2018); (b) MARS (Goad, 2018); (c) Living SeaWalls (Volvo, 2018); (d) Wave Break (Goad, 2022); (e) Snapper Reef Unit (SOI, 2012); (f) Boskalis Reef (Boskalis, 2017); (g) Hanging Fish House (Schofield, 2020a); (h) 3D ReefVival (Reef Design Lab, 2017); (i) X-Reef (Calanques National Park) (XtreeE, 2017); (j) Biomimetic Reef (Cap D'agde) (Dupuy de la Grandrive, 2018); (k) X-Coral (Oren, 2019); (l) 3DPARE (Hall *et al.*, 2018); (m) Recif'Lab L1 (Seaboost Ecological Engineering, 2021); (n) 3D-Printed Reef Tiles (ArchiReefs, 2020); (o) InnovaReef (Assava Dive Resort, 2020); (p); Recif'Lab L2 (Recif'Lab, 2022, p. 2)
Source: Figure by authors

and 39 publications and reports obtained from the website of the manufactured companies and institutions. The review focused solely on ARs manufactured through AM technologies (either directly fabricated or assisted with mould casting) that have been deployed in marine environments such as natural reserves, degraded areas or subaquatic tourisms zones. Artificial substrates used in small-scale tests, like those in studies Chamberland *et al.* (2017), Levy *et al.* (2023), Matus *et al.* (2021) and Ruhl and Dixson (2019) were excluded from this work as they may not offer the same level of complexity and habitat diversity as larger ARs.

The review focused on ARs implemented from the first reported case in 2012 up to 2022. Given the advancements in AM, it is plausible that more cases exist, which have not yet been documented or lack sufficient scientific data for inclusion in this research.

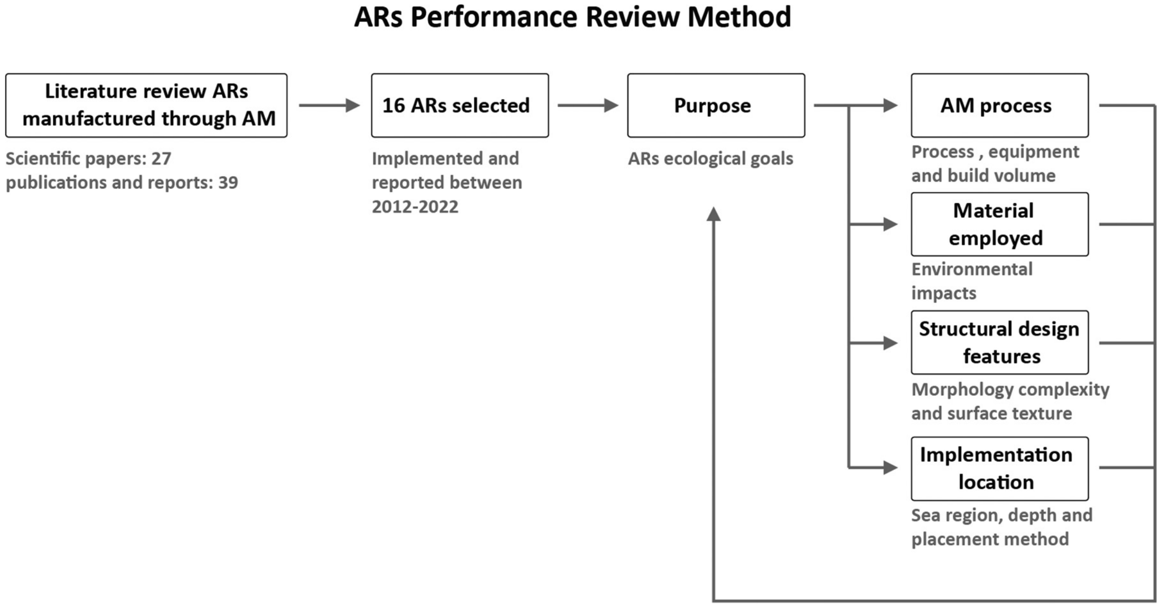
The systematic diagram in Figure 13 evaluates the performance of the ecological goals for each ARs, detailing the AM process used, materials used, structural design features and implementation locations.

2.1 Ecological goals identified according to the Practical Guidelines for the Use of Artificial Reefs

After selecting the AR cases, their purposes are identified (as defined by the authors in the referenced publications) and compared against the ten ecological goals outlined in the Practical Guidelines for the Use of Artificial Reefs (PGUAR) (Scarcella *et al.*, 2015). The identified purposes include:

1 protecting sensitive habitats from fishing industry activities;
2 restoring degraded habitats;
3 mitigating habitat loss;
4 enhancing biodiversity;
5 providing shelter to marine populations during their life stages;

Figure 13 The systematic method review of ARs that describes the process of scientific paper selection and their analysis to evaluate the performance according to the purpose



Source: Figure by authors

6. providing new substrates for benthic communities to settle on them;
7. enhancing professional and recreational diving areas;
8. promoting research and the educational field;
9. creating potential networks of MPAs; and
10. enhancing coastal erosion protection.

2.2 Additive manufacturing process used for artificial reefs

The parameters and variables of the AM process, presented in Table 2, are used to classify the manufacturing methods of the ARs.

For the dimension size and weight of unit modules that work as an assembly, average values were considered due to the design variations between each module. In some instances, the FFF process may be used to 3D print units for subsequent mould casting, where developed mortars will be poured. The weight and dimensions of ARs are intrinsically linked to the required machinery and logistics for implementation, impacting the overall costs and CO_2 emissions. Larger and heavier ARs require transportation and a crane boat for submersion.

In addition, the kinematic design category used to manufacture each AR, whether cartesian, delta or robot arm, was also identified and reviewed.

2.3 Classification of the material selection used to build artificial reefs

The parameters and variables of material selection, as presented in Table 3, are used to classify the ARs. The material used is critical for biological applications as it can directly or indirectly influence the impact on target species and the environment, contribute to a circular economy and determine the durability of the ARs, as well as their suitability for developing printable mortar. This classification considers the base material, aggregates, binders and additives (subject to the availability of the data information in the literature).

2.4 Structural design features incorporated to the artificial reefs

The ability of ARs to create complexity and/or mimic the marine environment significantly influences species' behaviour and interactions within the structure. Three indicators analysed in Table 4, help to establish structural features based on their shape, function and design pattern. Regarding to the importance of ARs shape for performance evaluation, two classifications were applied to the cases:

1. Geometric: Recognised geometric volumes or variations of them, with straight faces, symmetrical patterns, sharp edges and generally shapes not found in nature.
2. Irregular: Asymmetrical patterns, predominant curves and the absence of edges or straight faces, which mimic natural reefs.

One of the primary functions of ARs is to provide habitat for different marine organisms. The morphology and structural complexity play an important role in meeting the ecological goals. The ARs shape complexity offers hiding spots and microhabitats for a diverse array of marine species. These features include sheltering zones to protect species from predators, overhangs and ledge areas to provided shaded zones for specific organisms, and a rough surface texture to provide settlement substrates for benthic species.

Some studies introduced computer algorithms to create lattice structures (repeating patterns forming 3D shapes),

Table 2 Variables and specifications under analysis of AM process methods used to build ARs

AM process			3D printer	Manufacturing purpose		Typology		Dimension	Weight
FFF	BJ	PDM	Equipment	Moulding process	Final shape	Unit	Assembly	L × W × H (m^3)	(kg)

Source: Table by authors

Table 3 Variables and specifications under analysis of AM materials used and their environmental impacts or concern

Material (specification)				Environmental impacts
Cementitious	Ceramics	Geopolymers	Polymers	Marine life

Source: Table by authors

Table 4 Variables and specifications under analysis of ARs morphology features and design pattern

Shape		Function		Design pattern
Geometric	Irregular	Shelter Holes, crevices, tunnels and overhangs	Settlement Rough surface, texture	Path algorithm Lattice structure

Source: Table by authors

textures and self-supporting patterns through PDM controlled material deposition (Estévez and Abdallah, 2022) or through tool path planning (Hergel *et al.*, 2019). This novel method enhances paste material viscosity to create textures, thereby increasing the roughness essential for the settlement of marine organisms within micro-habitat. The diversity of structural elements per unit area, positively correlates with increased biodiversity (Huston, 1979; Kovalenko *et al.*, 2012).

An effectiveness evaluation ranking was implemented for the AR cases to assess how well their designs and materials align with the intended ecological goals. This evaluation considered various parameters, including design, material, monitoring techniques and manufacturing costs. The scoring system is as follows: 0 = ineffective, indicating that the evaluation parameter does not apply or fails to meet the required function; 1 = moderately effective, where the ARs partially meets the established function; and 2 = highly effective, meaning that the ARs fully serves its intended purpose.

2.5 Implementation climate zone preferences and deployment methods of artificial reefs

To identify relevant aspects of the habitat and implementation of AR methods, they were classified based on the parameters presented in Table 5.

ARs are placed in different sea regions: tropical (up to 25° latitude) and temperate (up to 60° latitude) and may be deployed at different depths depending on the specific purpose of each case. The geolocation categorised by climate regions and countries has been reviewed to identify where most implementations occur.

Table 5 Variables and specifications under study of ARs climate zone of implementation

Climate zone		Depth zone	Target species	Placement zone		
Tropical	Temperate	(m)	Coral fish bivalves	Sediments	Floating	Attached

Source: Table by authors

The deployment method can be categorised in three modalities of implementation: sediments zones (subtidal or marine soft bottom), predominantly where natural reefs are degraded or absent; floating structures, similar to aquaculture method, anchored and easily monitored by buoys; and attached to existing marine structures, such as seawalls or shoreline protections.

3. Results

3.1 Artificial reef purpose and ecological goals

The study identified primary and secondary ecological purposes in the manufacture of the 16 ARs using AM methods, presented in Table 6. The purpose indicator was obtained from the author's references and publications. According to the PGUAR, the results demonstrated that all ARs cases aimed to enhance biodiversity: 15 ARs (94%) provided new substrates for the settlement of benthic communities; 13 ARs (76%) aimed to mitigate habitat loss; 12 ARs (70%) provided shelter to marine life and promoted ongoing research, monitoring and education in this field; 8 ARs (47%) aimed to restore degraded habitats and establish a network of MPAs; 6 ARs (35%) promoted professional and recreational diving or snorkelling areas; 3 ARs (17%) targeted the protection of sensitive habitats from fishing activities; and a single case (5%) focused on enhancing coastal erosion protection.

All ARs proposed more than four ecological goals, reflecting an ambition to address a broad spectrum of ecological concerns, not just enhancing biodiversity – the primary goal of AR manufacturing – but also adding new features like coastal protection. The 3D ReefVival was the most successful, achieving eight of the ten ecological goals outlined by PGUAR.

Table 6 Identification of the main and secondary purposes to develop and implement ARs manufactured through additive manufacturing technologies and its correlation with the objectives determined by the Practical Guidelines for the Use of Artificial Reefs (PGUAR)

No.	ARs	Main purpose	Secondary purposes	Reference	PGUAR
(a)	Hope 3D	Preserve threatened coral species across the entire reef model in Hol Chan Marine Reserve (MPA)	Attract fish communities with an eco-friendly material approach	Cowo (2018); Suchin (2019, 2018)	(3, 4, 7, 9)
(b)	MARS	Develop a coral farming structure to encourage the natural recruitment of juvenile coral and facilitate transplantation	Rebuild reef structures Habitat protection for other species	Goad (2018), Reef Design Lab (2019)	(2, 3, 4, 5, 6, 8)
(c)	Living SeaWalls	Enhance biodiversity and ecological function on urban structures	Educational programs to promote science Shelter juvenile fish Provide additional habitat opportunities to fish, seaweed, oysters, other molluscs, lace corals, sea squirts and sponges Provide moisture retention and cooling through water-retaining features	Reef Design Lab (2018), Torres-Pulliza *et al.* (2020)	(1, 2, 3, 4, 6, 8)
(d)	Wave Break	Provide coastal protection and habitat enhancement	Promote snorkelling activities Reduce waves force and prevent further erosion Encourage natural recruitment of marine organisms Promote mussel and oyster colonisation	Goad (2022), VRCA (2022)	(4, 5, 6, 7, 8, 10)
(e)	Snapper Reef Unit	Replace damaged reef structures to provide habitat diversity	Build the first ARs through AM technologies	Gardiner (2011), Reef Arabia (2012)	(2, 3, 4, 5, 6)
(f)	Boskalis Reef	Improve ecology and the quality of seawater at Monaco Larvotto Reserve (MPA)	Promote ecosystem restoration by creating habitat for macro-invertebrates and fish Mimic natural habitat	Jacqueline *et al.* (2017); Riera *et al.* (2020, 2018)	(3, 4, 5, 6, 8, 9)
(g)	Hanging Fish House	Accommodate fouling marine organisms and juvenile fish	Provide shelter for juvenile fish	Schofield (2020a, 2020b)	(4, 5, 6, 8)
(h)	3D ReefVival	Assist native oyster recruitment and restoration	Assessing the effectiveness of the material and technology Experimental research Promote colonisation of encrusting sessile organisms Recovery shellfish reef	Kardinaal *et al.* (2020), WWF Netherlands (2018)	(1, 2, 3, 4, 5, 6, 8, 9)
(i)	X-Reef	Protect biodiversity and recreate ecological habitat in the Calanques national park (MPA)	Mimic Coralligenous habitat in the Mediterranean Research study	Salaün *et al.* (2020); XtreeE (2017)	(3, 4, 5, 6, 9)
(j)	Biomimetic reef	Promote underwater biodiversity to Mediterranean coastal fauna and flora in Cap d'Agde (MPA)	Facilitate the resilience of fish Enhance surface orientation for colonisation	Salaün *et al.* (2020); XtreeE (2019)	(3, 4, 5, 6, 9)
(k)	X-Coral	Replace part of a damaged reef to attract fish	Research new morphologies to form marine habitats	Berman *et al.* (2023)	(4, 6, 7, 8)

(***continued***)

Table 6

No.	ARs	Main purpose	Secondary purposes	Reference	PGUAR
(l)	3DPARE	Enhance biodiversity and ecosystem services	Stimulate colonisation to the recovery of damaged ecosystems Evaluate the environmental impact of the materials used Research monitoring study	Hall *et al.* (2018), Interreg (2019); Yoris-Nobile *et al.* (2023)	(4, 5, 6, 8)
(m)	Recif'Lab L1	Provide marine surface buoys (replacing cement-filled tires) to mark coastal strip of 300 m	Promote marine biodiversity and attract juvenile fish species in Agathoise MPA	Denolly (2020); Recif'Lab (2022); Seaboost Ecological Engineering (2021)	(4, 5, 7, 9)
(n)	3D printed reef tiles	Restore and enhance coral survivorship and growth in Hoi Ha Wan Marine Park (MPA)	Prevent sedimentation build-up Promote marine life education	(ArchiReefs, 2020; Lange *et al.*, 2020)	(2, 3, 4, 6, 8, 9)
(o)	InnovaReef	Restore the coral ecosystem through the promotion of coral larval settlement and juvenile transplantation	Restore and enhance the sea fertility of Thailand's marine ecosystem	Chulalongkorn (2020)	(1, 2, 3, 4, 6, 8)
(p)	Recif'Lab L2	Preserve marine biodiversity in Cap d'Adge MPA, promoting specific divers interested species (fish, octopus and lobster) and reduce deteriorate natural ecosystem	Promote Scuba diving Target different life stages species	Seaboost Ecological Engineering (2022)	(3, 4, 5, 6, 7, 8, 9)

Notes: (1) Protecting sensitive habitats from fishing industry activities; (2) restoring degraded habitats; (3) mitigating habitat loss; (4) enhancing biodiversity; (5) providing shelter to marine populations during their life stages; (6) providing new substrates for benthic communities settle on them; (7) enhancing professional and recreational diving areas; (8) promoting research and education field; (9) creating a potential network of marine protected areas; and (10) enhancing coastal erosion protection
Sources: Scarcella *et al.* (2015); Table by authors

3.2 Artificial reef manufactured process

The results indicated a predominance of PDM process in AR manufacturing. For cases using FFF, two different approaches were identified: to assist the creation of casting moulds for cementitious or ceramic mortars [e.g. MARS, Living Seawalls and Wave break (Goad, 2022; Reef Design Lab, 2019, 2018)] and to produce the final shape through an assembly method (e.g. Hope 3D (Suchin, 2018)).

Technical data of AR manufacturing is presented in Table 7. In terms of the AM equipment and the kinematic design used, the cartesian method was the most used for material deposition, revealed in nine AR cases (Figure 14).

The study identified three AR manufacturing typologies, detailed in Figure 15: the independent unit reef (eight cases), the most common but limited by AM equipment print volume; the composed unit reef (two cases), which allows for the largest ARs reported to date; and the assembly reef (six cases), offering high scalability and potential to expand the coverage area.

The typology of manufacturing is closely linked to logistics and implementation costs, as heavier and larger ARs require heavy machinery for transport and deployment, thus increasing costs (Yoris-Nobile *et al.*, 2023). Conversely, modular assembly reef systems, like the 3D printed reef tiles, manually deployed by small boats and divers (ArchiReefs, 2020) eliminates the need for such machinery, offering a more accessible solution for communities (Reef Design Lab, 2019).

The results demonstrated that assembly reef units weighed between 3 and 40 kg per module, significantly lighter than the independent units, which ranged from 500 to 1,000 kg. The composed unit reef, however, allowed for the manufacturing of mega-structures weighing up to 105,000 kg, as it combined several modules into one large AR, making it the heaviest and largest recorded to date (Seaboost Ecological Engineering, 2022).

3.3 Artificial reef material selection

Regarding the selection of materials presented in Table 8, cementitious mortar was the most used, featuring in ten AR cases (62%); ceramics were used in 5 (31%); and geopolymers and polymers in 1 (6%). The data indicates a trend towards incorporating recycled materials (Reef Design Lab, 2018), bio-residues such as seashells (Goad, 2022; Yoris-Nobile *et al.*, 2023), bio-based resins derived from bamboo (Schofield, 2020a) and marine cement aimed to replace Portland cement, the primary source of CO$_2$ emission in cement productions (Dennis *et al.*, 2018). The aggregates include pozzolans (Meyer, 2009), waste materials (Cuadrado-Rica *et al.*, 2016; Yang *et al.*, 2005), ceramics, end-of-life cement and natural fibres (Pandey *et al.*, 2010). The incorporation of pozzolans can lower the surface pH of cement (Fernández Bertos *et al.*, 2004), a critical factor for marine colonisation. One project (Suchin, 2018) used polylactic acid (PLA), a biodegradable plastic known for its minimal negative environmental impact, although its degradability remains under question (Tarazi *et al.*, 2019). Some studies revealed that PLA can attract marine bacterial communities (Birnstiel *et al.*, 2022; Cheng *et al.*, 2021).

Some ARs have raised concerns about the marine environment due to the materials used. Table 9 outlines the main concerns and impacts of these materials on marine ecosystems, identifying specific issues raised by certain ARs.

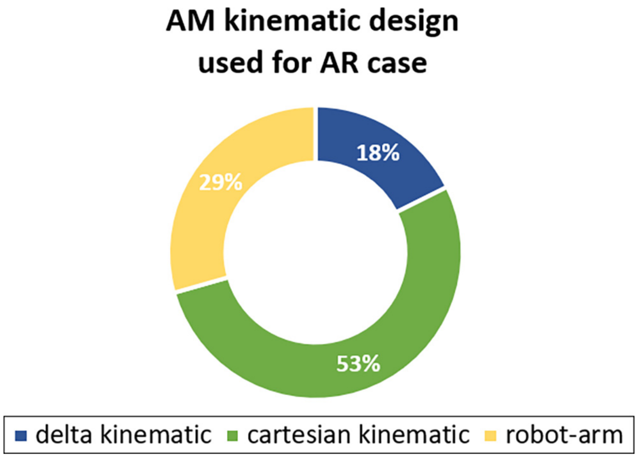
Hope 3D project used PLA plastic material and it was placed in mangrove and sea grass habitats (Hol Chan Marine Reserve, 2018). Despite PLA being a bio-based polyester derived from renewable sources like sugarcane or cornstarch (Balla *et al.*, 2021), it is nor recommended for marine environments because of its biodegradable condition. Although there are no scientific updates about its current status on the seafloor, various studies have documented that PLA may affect marine species (Ali *et al.*, 2023).

Table 7 ARs technical classification through their AM technology

No.	ARs	AM process	3D printer equipment	Dimension L × W × H (m^3)	Weight (kg)	Reference
(a)	Hope 3D	FFF	Robo 3D r1+	0.1 × 0.1 × 0.1 (un) 1 × 1 × 2 (as)	100–150 (as)	Suchin (2019, 2018)
(b)	MARS	FFF	Desktop FFF	0.4 × 0.4 × 0.6 (un) 1.8 × 1.7 × 1.7 (as)	40 (un) 2,000 (as)	Reef Design Lab (2019)
(c)	Living Seawalls	FFF	Makerbot	0.5 × 0.5 × 0.5 (un)	23–30	Reef Design Lab (2018)
(d)	Wave Break	FFF	BigRep One	2 × 2 × 1 (un)	300–400	Goad (2022)
(e)	Snapper Reef Unit	BJ	D-shape	1 × 1 × 1 (un)	500	Reef Arabia (2012)
(f)	Boskalis Reef	BJ	D-shape	2 × 2 × 1 (un)	2,500	Boskalis (2017)
(g)	Hanging Fish House	BJ	Zprinter 310 plus	0.1 × 0.1 × 0.5 (un)	3 (un) 9 (as)	Schofield (2020a)
(h)	3D ReefVival	BJ	D-shape	0.5 × 0.5 × 1.2 (un)	1,000	Kardinaal *et al.* (2020)
(i)	X-Reef	PDM	ABB	1.1 × 0.9 × 1.1 (un)	900	XtreeE (2017)
(j)	Biomimetic Reef	PDM	ABB	0.9 × 1.6 × 1.3 (un)	550	XtreeE (2019)
(k)	X-Coral	PDM	LDM-Wasp 3L Clay Tank	1 × 1 × 3 (as)	20 (un)	Berman *et al.* (2023)
(l)	3DPARE	PDM	Wasp 3MT	1 × 1 × 1 (un)	1,000	Yoris-Nobile *et al.* (2023)
(m)	Recif'Lab L1	PDM	ABB	0.9 × 0. 9 mx 1 (un)	1,000	Seaboost Ecological Engineering (2021)
(n)	3D Printed Reef Tiles	PDM	ABB 6700	0.6 × 0.6 × 0.4 (un)	10	Lange *et al.* (2020)
(o)	InnovaReef	PDM	Wasp	1.5 × 1 × 0.7 (un)	700	Chulalongkorn (2020)
(p)	Recif'Lab L2	PDM	ABB CyBe RC	6 × 8 × 6.5	105000	Seaboost Ecological Engineering (2022)

Notes: fused filament fabrication (FFF), binder jetting (BJ) or material extrusion process through paste deposition modelling (PDM); 3D printer equipment; dimension and weight considered for a single unit (un) and/or the assembly reef (as)
Source: Table by authors

Figure 14 Diagram illustrates the AM kinematic design used to AR cases determined by their percentage



Source: Figure by authors

It becomes brittle because of the environmental stress and the infiltration of impurities, which harms marine life, affects fertilisation and leads to biological accumulation. Slower degradation increases the risk of marine species ingesting it, whereas faster degradation is less sustainable in terms of a circular economy. No reports have been documented regarding fish seeking refuge within the PLA ARs. Regarding the inhibitory effect of PLA on algae growth, as described by some authors in the previous table, this case revealed the successful formation of algae covering the structure.

3DPARE has raised concerns about the mortars developed using cement and geopolymer-based materials. These materials induce the elevation in the pH levels of the surrounding surface, increasing the pH from the normal values of 7.4 to over 10 within a few minutes. This alkaline effect can negatively impact various organisms. However, this initial pH elevation may be considered as a potential strategy for anti-fouling defence. The pH increase affect mainly the surface area surrounding the ARs. The large volumes of seawater in the ocean effectively balance the early pH "toxicity" effects caused by geopolymers and cement through dilution. After seven days in seawater, the adverse impact on microorganism colonisation is mitigated (Ly *et al.*, 2021).

Boskalis project conducted a comparative analysis of dolomite and cement materials used during the manufacture of the ARs. It was revealed that bacterial communities form biofilms on both materials. However, the biofilm formation occurs at slower rate on cement-based aggregates (Kramer and Lescinski, 2017).

3.4 Structural complexity features

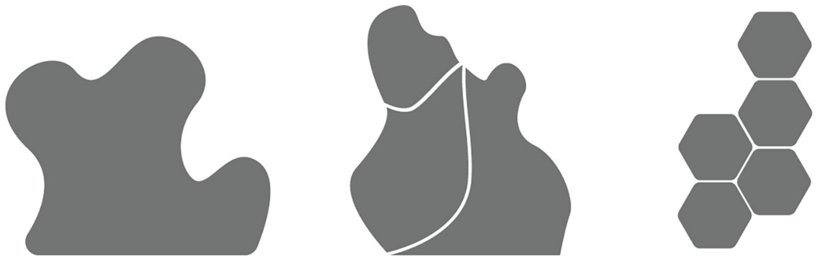
Among the 16 ARs, 3 structural design features were identified in Figure 16: shelter and settlement features for ecosystem function and shape feature for environmental integration.

To provide shelter for various species, ARs should incorporate holes, internal tunnels and overhang zones. These features offer refuge from marine currents and predators (Jung *et al.*, 2022). The results revealed that 8 ARs integrated holes for smaller species like fish, crabs and shrimps; 6 ARs incorporated internal tunnels for larger species such as octopuses, crabs and large fish; and 14 ARs included overhang areas for starfish and flatworms (Hall *et al.*, 2018). Four ARs combined these three shelter features, enhancing habitat diversity with different sizes and lengths of holes and tunnels (Boskalis, 2017; Hall *et al.*, 2018; Reef Design Lab, 2017; Seaboost Ecological Engineering, 2022).

The analysis of various geometries in the case studies identified five common structural design patterns across all ARs (Figure 17):

1. Modular spatial assembly: two cases (Hope 3D and MARS) used a LEGO-like system for easy manufacturing, transport and assembly, offering scalability.
2. Hexagonal shape and biomimetic textures: two cases (3D Printed Reef Tiles and Living Seawalls) used hexagonal plates with biomimetic textures inspired by coral brain and mangroves. The design shape not only increased the surface area available for colonisation but also facilitated spatial expansion. The 3D Printed Reef Tiles were designed for horizontal expansion on the seafloor, whereas the Living

Figure 15 AR build typology classification by three design features



(a)
Wave break | Snapper Reef Unit | Boskalis Reef | 3D ReefVival | X-Reef | Biomimetic Reef | 3D Pare | InnovaReef

(b)
Recif'Lab L1 | Recif'Lab L2 | X-Coral |

(c)
Hope 3D | MARS | Living SeaWalls | Hanging Fish House | 3D Printed Reef Tiles

Notes: (a) Independent unit reef; (b) composed unit reef; (c) assembly reef
Source: Figure by authors

Table 8 Materials used in the manufacture of the ARs

No.	ARs	Material specification	Reference
(a)	Hope 3D	Polylactic acid (PLA)	Suchin (2018)
(b)	MARS	Ceramic filled with cement and steel reinforcement	Reef Design Lab (2019)
(c)	Living Seawalls	Glass fibre reinforced cement (with recycled polymer fibres) Stainless steel rods drilled for installation	Living Seawalls (2018), Reef Design Lab (2018)
(d)	Wave Break	Cement and recycled shell aggregate	Goad (2022)
(e)	Snapper Reef Unit	Magnesia cement (binder), dolomite sand and sedimentary rocks (aggregate)	Dini and Monolite (2016)
(f)	Boskalis Reef	Dolomite sand (material base), magnesium oxide (binder)	Jacqueline *et al.* (2017)
(g)	Hanging Fish House	Calcium carbonate (limestone) and bio-based resin derived from bamboo	Schofield (2020a)
(h)	3D ReefVival	Dolomite sand, trass flour (Tubag^{TM}), white cement (CEM I/II) and fresh tap water	Colsoul *et al.* (2020), Kardinaal *et al.* (2020); Reef Design Lab (2017), Tubag (2024)
(i)	X-Reef	Cement LafargeHolcim	Holcim (2024), XtreeE (2017)
(j)	Biomimetic Reef	Cement Vicat.	Vicat (2024), XtreeE (2019)
(k)	X-Coral	Atomised clay mixture (Goerg and Schneider Body 0311) composed of iron oxide (6.5%), sodium-silicate (binder)	Berman *et al.* (2023)
(l)	3DPARE	Cement mortar Cement CEM III/B, fly ash, kaolin, limestone, seashells, glass Geopolymer mortar Fly ash, sodium hydroxide (NaOH), nano-silica, micro-silica, limestone, seashells and glass	Yoris-Nobile *et al.* (2023)
(m)	Recif'Lab L1	Cement Vicat	Seaboost Ecological Engineering (2021); Vicat, 2024)
(n)	3D-Printed Reef Tiles	Red terracotta clay (P1331, Potterycrafts Ltd), crystalline silica	Lange *et al.* (2020)
(o)	InnovaReef	Recycled cement	Chulalongkorn (2020)
(p)	Recif'Lab L2	Cement Vicat	Seaboost Ecological Engineering (2022)

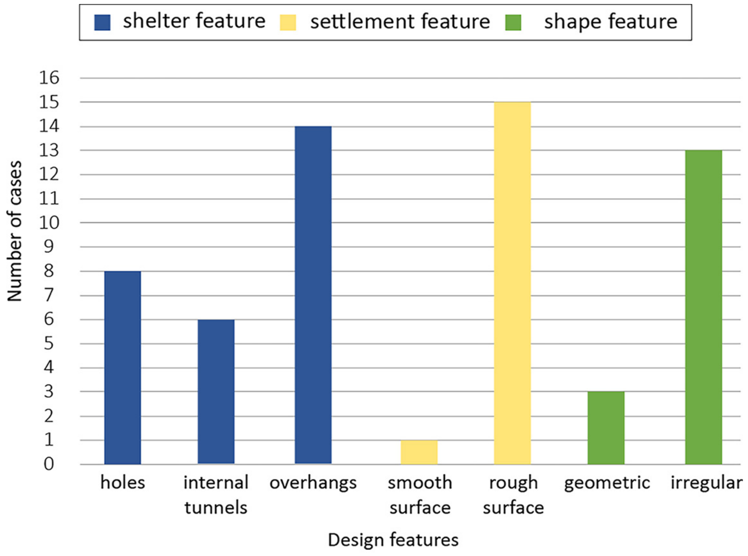
Source: Table by authors

Table 9 Environmental impact and associated concerns arising from the materials used in AM to build ARs

Main material used	Marine environmental impacts/concern	Reference
Polylactic acid (PLA)	PLA gradually disintegrates into microplastic in underwater conditions, inhibiting algae growth and reducing the survival of up to 40% of phytoplankton. While it has a minimal effect on molluscs, it can adversely affect fish behaviour through ingestion, resulting in negative impacts	Ali *et al.* (2023)
Cement Portland	Cement, composed of calcium carbonate, is conducive to the colonisation of benthic calcareous skeletons. However, a surface with high alkalinity (pH 12–13) might inhibit the settlement of species that are intolerant to such alkaline conditions	Natanzi *et al.* (2021)
Shell aggregate	Enhances the circular economy and reduce carbon dioxide emissions. The use of oyster shell waste increases surface porosity due to its material properties, thereby facilitating the initial biological attachment	Hou *et al.* (2016), Kong *et al.* (2022)
Fly ash	Its specific constituents like selenium in high concentrations has the potential to impact the early life stages of fish. Containing a range of metals and other elements, fly ash can become toxic to biological ecosystems at high concentrations	Greeley *et al.* (2012)
Terracotta clay and ceramics	Its composition featuring non-toxic oxides and a neutral pH, is ideal for marine environments applications, supporting biological productivity and ensuring no adverse effects	Kalam *et al.* (2018)

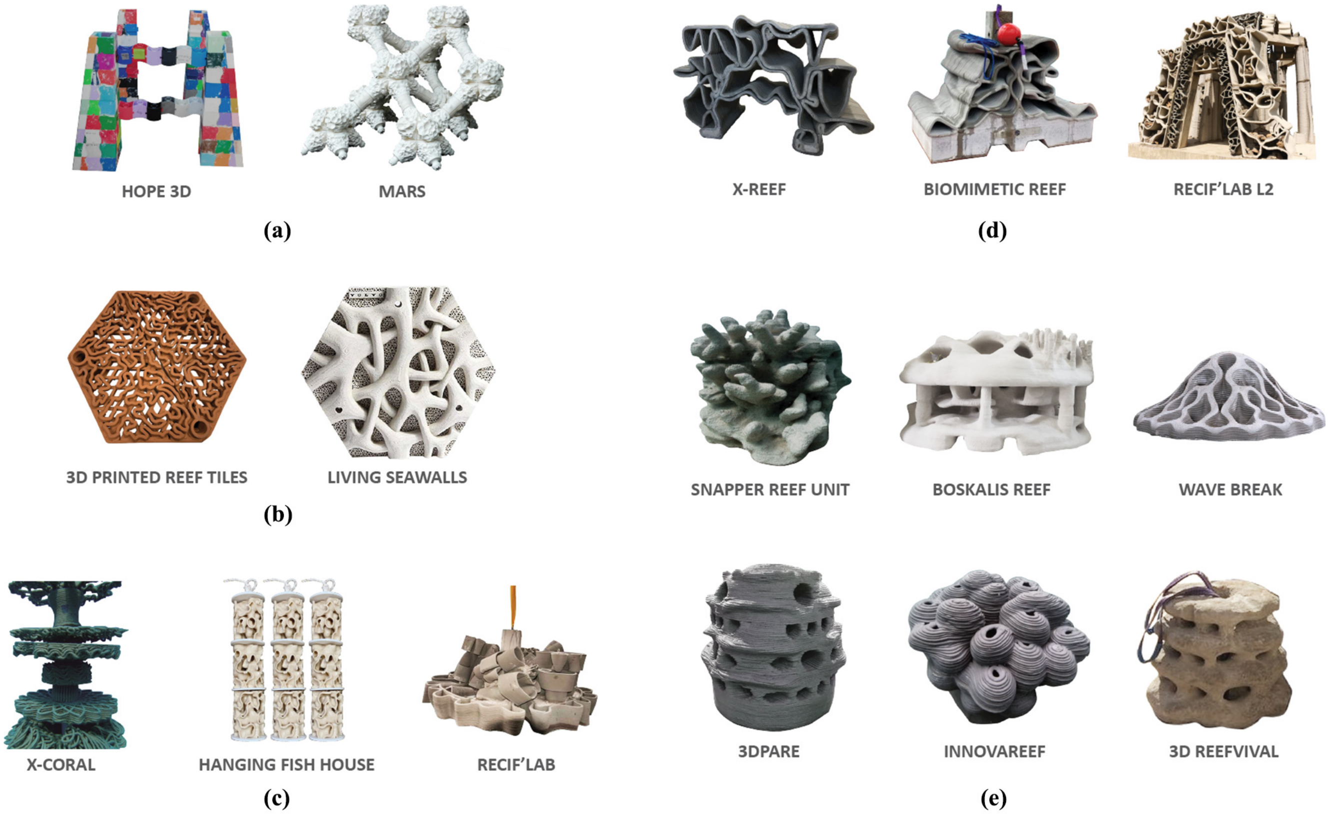
Source: Table by authors

Figure 16 Graph illustrates AR structural design features, highlighting shelter, settlement and shape characteristics identified in all the cases



Source: Figure by authors

Figure 17 Identification of five common structural design features found in AR cases



Notes: (a) Modular spatial assembly; (b) hexagonal shape and biomimetic textures; (c) repeating pattern of stacked elements; (d) random contouring lines extruded; (e) solid unit with random holes, tunnels and intricate zones
Source: Figure by authors

Seawalls were intended for vertical expansion on port walls, demonstrating versatile applications and functions.

3 Repeating pattern of stacked elements: three cases (X-Coral, Hanging Fishing House and Recif'Lab) used abstract shapes in modules for vertical expansion.
4 Random contouring lines extruded: three cases (X-Reef, Biomimetic Reef and Recif'Lab L2) used the extrusion method using random curved lines to shape the reef units. This technique created multiple internal tunnels of various sizes, providing shelter for different species.
5 Solid unit with random holes, tunnels and intricate zones: six cases (Snapper Reef Unit, Boskalis Reef, Wave Break, 3DPARE, Innovareef and 3D ReefVival) demonstrated a trend of ARs manufacturing individual solid units that worked independently. These units were designed with random tunnels, holes, intricate zones and surface textures, creating diverse habitats within a single structure. They can work independently or be combined with multiple units to cover a larger area.

The ARs vary in size but share common design elements that support similar biological functions. In terms of physical characteristics, such as the effect of material colour, only two cases, 3D Printed Reef Tiles and Hope 3D, were notable for their unique red-brown and vibrant material colours. The rest used neutral colours from materials like cement, sand and ceramics. However, the potential impact of ARs colour on species colonisation or attraction remains unexplored.

According to settlement features, the adhesion phenomena are crucial for marine community colonisation, such as algae, corals and molluscs (Petersen *et al.*, 2020). Only one AR opted for a smooth surface, whereas the others implemented rough surfaces with varying patterns and depths to facilitate organisms attachment (Colsoul *et al.*, 2020). A novel method used PDM, to create a path lattice matrix through parametric design tools to control the ceramic material's spatial deposition (Berman *et al.*, 2023). Three texture typologies were identified in Figure 18: random soft crevices designed in 3D CAD software; a sandy roughness characterised by the BJ process used, for enhance surface texture; and rough layers, extruded through a path lattice matrix, creating a textured relief whose detail is determined by the extruder's diameter.

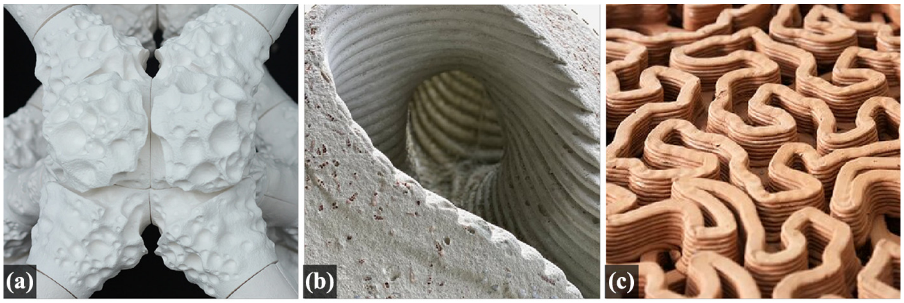
Two shape configurations, defined by previously reviewed functional features, were identified as geometric and irregular. Two ARs (Lange *et al.*, 2020; Reef Design Lab, 2018) used hexagonal panels (a recognised geometric pattern) to enable modular and scalable expansion. However, they also incorporated natural texture elements such as branches/ramifications (Reef Design Lab, 2018) and a brain pattern inspired by the *Diploria labyrinthiformis* coral species (Lange *et al.*, 2020), demonstrating the potential to combine shape configurations. The versatility of AM process, allows the customisation of solutions through variations in morphology and texture, as illustrated in Figure 19. This adaptability can address a wide range of species, implementations regions and specific purposes.

3.5 Effectiveness of the design for meeting ecological goals

The Hope 3D case demonstrated the lowest effectiveness, scoring only 6, in its primary goal of preserving threatened coral species. The project failed to identify suitable structural zones for coral transplantation and lacked the necessary rough surfaces and environmentally friendly materials for coral settlement. While the intention was to use a biodegradable polymer to reduce environmental impact compared with petroleum-based polymers, concerns were raised due to the biodegradable condition of the PLA material and the potential ingestion of plastic debris by marine fish. The ARs partially succeeded in attracting fish species, which was established as a secondary ecological goal and reported in the weeks following implementation. However, it is challenging to ascertain whether this observer trend has persisted over time due to the absence of updated information.

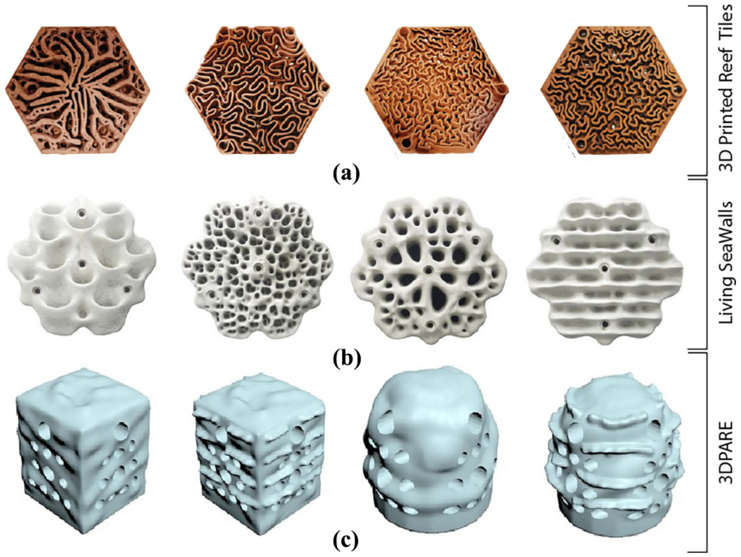
The Hanging Fish House scored 8, indicating moderate effectiveness. Its complex geometry algorithms, both in terms of volume and internal spaces, contribute to enhancing biodiversity and align with the ecological goal of accommodating fouling organisms and juvenile fish. However, the design faces challenges, as its complex shape initially provided small fish refuges but became covered with fouling organisms in a short time, compromising its "fish house" functionality. In contrast, the ARs, mimicking coral shapes and using coral calcium carbonate as raw material, provide a smooth surface with relief features for settlement functions.

Figure 18 Typologies comparison of surfaces with biomimetic textures identified in the ARs



Notes: (a) MARS – Alex Goad; (b) Wave Break – Reef Design Lab; (c) 3D-Printed Reef Tiles – Archireef
Source: Figure courtesy of Lange *et al.* (2020) and Reef Design Lab (2018)

Figure 19 AR comparison cases about the versatility of AM to manufacture and customize texture and shape variables for different biological purposes



Notes: (a) 3D printed reef tiles; (b) Living Seawalls; (c) 3DPARE
Sources: Figure courtesy of Lange *et al.* (2020); Reef Design Lab (2018); 3DPare (2018); Hall *et al.*, 2018; L. Vozzo *et al.*, 2019 and Technion, 2019

X-Coral, InnovaReef and Snapper Reef Unit achieved a moderate effectiveness score of 10. X-Coral aimed to mimic the structural patterns of *Hexacorallia* coral variations, exploring diverse morphologies and algorithms of clay material extrusion to enhance marine habitats. The variety of module shapes increased habitat complexity, aligning with the goal of attracting fish communities. However, vertical modules lacked stability and durability compared with the robust cement structure of InnovaReef. A notable advantage is the easily modular design system, like the Hanging Fish House and Hope 3D ARs. This system facilitates implementation and reduces deployment costs.

InnovaReef ARs aims to replicate the structural form of coral reefs, aligning with its intended purpose, but it lacks on specific biomimetic features. The ARs do not fully achieve their primary ecological goal, which is to restore coral ecosystems by promoting the settlement of coral larvae and juvenile transplantation. This limitation primarily results from the absence of appropriate zones for these purposes. While the structure offers a textured and rough surface to facilitate benthic settlement, the inclusion of internal holes and the composition of the cement material do not promote coral larvae settlement.

Snapper Reef Unit was the first AR manufactured with AM technologies. Beyond ecological goals, the primary challenge was to demonstrate the effectiveness of AM to build a structurally complex unit that could enhance marine biodiversity. The robust, dolomite sand-based structure features numerous branches of varying sizes and directionals levels, fostering marine biodiversity.

Recif'Lab L1 and Boskalis Reef both scored 11, indicating moderate effectiveness. While lacking biomimetic inspiration, their complex random shapes with various holes and tunnels serve ecological goals by promoting biodiversity and attracting juvenile fish. The structures offer multiple refuge zones for fish, and their weight and robust shapes enhance stability and durability, ensuring their effectiveness in fulfilling ecosystems functions.

3D ReefVival, X-Reef, Biomimetic Reef and Recif's Lab l2 all achieved a score of 12, indicating moderate effectiveness. None of these projects integrated waste materials into their formulations, and they also did not implement biomimetic design elements. X-Reef, Biomimetic Reef and Recif's Lab L2 aimed to mimic structures resembling the *Coralligenous* (reef habitat in the Mediterranean). However, the real intention was to recreate the marine ecosystems found in the Coralligenous habitat within the ARs, and not to mimic morphological elements from that habitat. All projects were well-designed to meet their ecological goals, including creating habitat for macro-invertebrates and fish, preserving biodiversity and enhancing fish resilience. The 3D ReefVival used specific hole sizes in four platforms connected by pillars and elevated from the seafloor to support native oyster recruitment and restoration. In addition, a rough surface was integrated to promote the colonisation of stationary organisms.

Regarding the post-processing operations of the different AM processes used, 3D ReefVival, which used BJ process, involved steps such as removing excess powder material, sintering and finishing. In contrast, the other AR cases that used cement extrusion only required drying the water content from the paste, reducing manufacturing steps and costs.

3DPARE achieved a high effectiveness score of 15. Its structural design, which includes larger-sized holes, was implemented to enhance biodiversity and ecosystem services. The ARs also considered mitigating the negative effects of sediment dynamics by elevating the positions of surface reliefs and internal tunnels. However, they feature rough surface reliefs and a robust geometric main shape (cube and cylindrical variations) without addressing any biomimetic design pattern.

MARS, Living Seawalls, Wave Break, 3DPARE and 3D Printed Reef Tiles achieved the highest effectiveness scores, ranging from 15 to 17. Each of them integrated biomimetic-inspired structural designs tailored to their specific ecological goals: MARS incorporated *Scleractinia* coral textures in the ARs to create underwater nurseries conducive to the attachment, settlement and growth of coral species; Living Seawalls expanded colonisation areas with customised panels inspired by mangroves, natural rockpools, sedimentary rocks, holdfast root structures and natural sandstone rocks; Wave Break, placed in the intertidal zone, mimicked rocky reefs with natural pools to mitigate wave forces with its robust dome shape and to foster marine organisms; and 3D Printed Reef Tiles drew inspiration from the stony coral species *Platygyra* for its textures. With the addition of three base legs, stability was ensured, preventing sinking into the seafloor and protecting against sedimentation. The texture is tailored to meet restoration needs.

The evaluation scores for each ARs, presented in Tables 10 and 11, were determined by ranking parameters across the following categories: material, design, monitoring and costs.

The evaluation of ARs involved assessing various parameters to determine how well their design and materials aligned with their ecological goals (Figure 20). Monitoring techniques were crucial for evaluating effectiveness and tracking changes over time. Projects that applied monitoring methods were considered. In addition, the AM process, design and size influenced cost reduction. The results revealed that five ARs were highly effective; ten ARs had moderate effectiveness and one AR showed low effectiveness.

3.6 Implementation location

The data collection revealed a global diversity of 16 ARs manufactured using AM technologies. However, this number is considerably lower than the overt 1,074 ARs identified in 71 countries build through traditional manufacturing processes (Ramm *et al.*, 2021).

Two ARs were implemented in multiple locations across various countries and different ocean regions. Living Seawalls were deployed in seven locations, including Australia, Singapore, Gibraltar and Wales, whereas 3DPARE was implemented in four locations across Portugal, France, Spain and the UK. The ARs were adapted and customised for each deployment zone, with adjustments to the texture and shape features to suit the respective habitat and ecological goals determined in each location.

There are two ARs projects that were implemented in various locations, countries and different ocean regions. Living Seawalls were placed in seven locations between Australia, Singapore, Gibraltar and Wales; and 3DPARE in four locations between Portugal, France, Spain and the UK. The projects were adapted for each deployment zone, adjusting texture and shape features to be appropriated for the habitat and purposes established.

Table 10 Evaluation ranking of ARs effectiveness considering the material and design used to assess the ecological goals proposed

	Evaluation of material and design category scores						
	Material			Design			
ARs No.	The material used positively contribute with no adverse impact on marine life	The material mixture integrates waste materials to promote circular economy	The material used exhibit high level of structural durability and longevity	The design geometry is inspired by biomimetic patterns, emphasising both texture and/or shape	The design incorporates rough surface to facilitate the settlement of organisms	The structural design features are implemented to meet the proposed ecological goals	Sub-total score
(a)	1	0	0	0	0	1	2
(b)	2	0	2	2	2	2	10
(c)	2	2	2	2	2	2	12
(d)	2	2	2	2	2	2	12
(e)	2	0	2	1	2	2	9
(f)	2	0	2	1	2	2	9
(g)	1	0	1	2	1	1	6
(h)	2	0	2	1	2	2	9
(i)	1	0	2	1	2	2	8
(j)	1	0	2	1	2	2	8
(k)	2	0	1	1	2	1	7
(l)	2	2	2	1	2	2	11
(m)	1	0	2	0	2	2	7
(n)	2	0	2	2	2	2	10
(o)	1	1	1	1	2	1	7
(p)	1	0	2	1	2	2	8

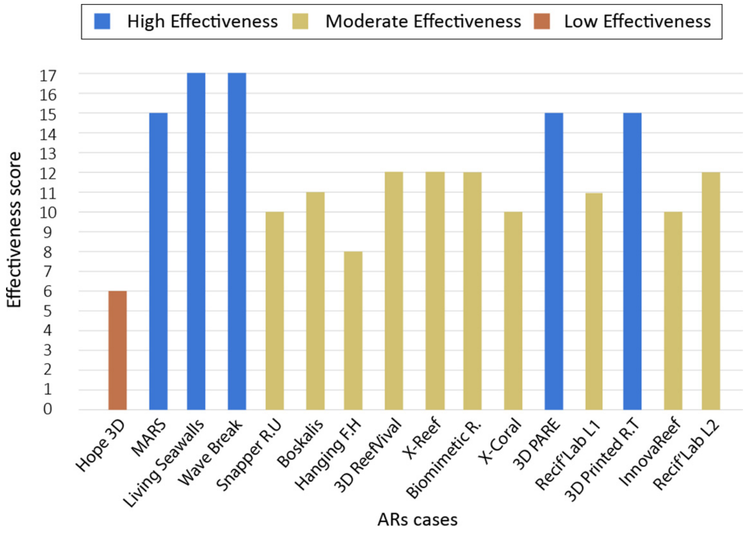
Notes: The score numbers consider 0 = ineffective; 1 = moderately effective; 2 = highly effective; (a) Hope 3D; (b) MARS; (c) Living Seawalls; (d) Wave Break; (e) Snapper Reef Unit; (f) Boskalis Reef; (g) Hanging Fish House; (h) 3D ReefVival; (i) X-Reef; (j) Biomimetic Reef; (k) X-Coral; (l) 3DPARE; (m) Recif'Lab L1; (n) 3D Printed Reef Tiles; (o) InnovaReef; (p) Recif'Lab L2
Source: Table by authors

Table 11 Evaluation ranking of ARs effectiveness considering the ongoing monitoring techniques and how the design and process may reduce manufacturing costs

	Evaluation of monitoring and cost category scores			
	Monitoring	Costs		
Ars No.	**Ongoing monitoring techniques are used to study the AR evolution**	**The design and size of ARs are efficiently managed without the need for heavy machinery, reducing associated costs for logistics**	**The AM process eliminates the need for post-processing finishing, reducing production and workforce costs**	**Sub-total score**
(a)	0	2	2	4
(b)	2	2	1	5
(c)	2	2	1	5
(d)	2	1	2	5
(e)	0	1	0	1
(f)	2	0	0	2
(g)	0	2	0	2
(h)	2	1	0	3
(i)	2	0	2	4
(j)	2	0	2	4
(k)	0	2	1	3
(l)	2	1	2	5
(m)	2	0	2	4
(n)	2	2	1	5
(o)	0	1	2	3
(p)	2	0	2	4

Notes: The score numbers consider 0 = ineffective; 1 = moderately effective; 2 = highly effective. (a) Hope 3D; (b) MARS; (c) Living Seawalls; (d) Wave Break; (e) Snapper Reef Unit; (f) Boskalis Reef; (g) Hanging Fish House; (h) 3D ReefVival; (i) X-Reef; (j) Biomimetic Reef; (k) X-Coral; (l) 3DPARE; (m) Recif'Lab L1; (n) 3D Printed Reef Tiles; (o) InnovaReef; (p) Recif'Lab L2
Source: Table by authors

Figure 20 The evaluation results of the effectiveness ranking of ARs based on design and material features in meeting ecological goals

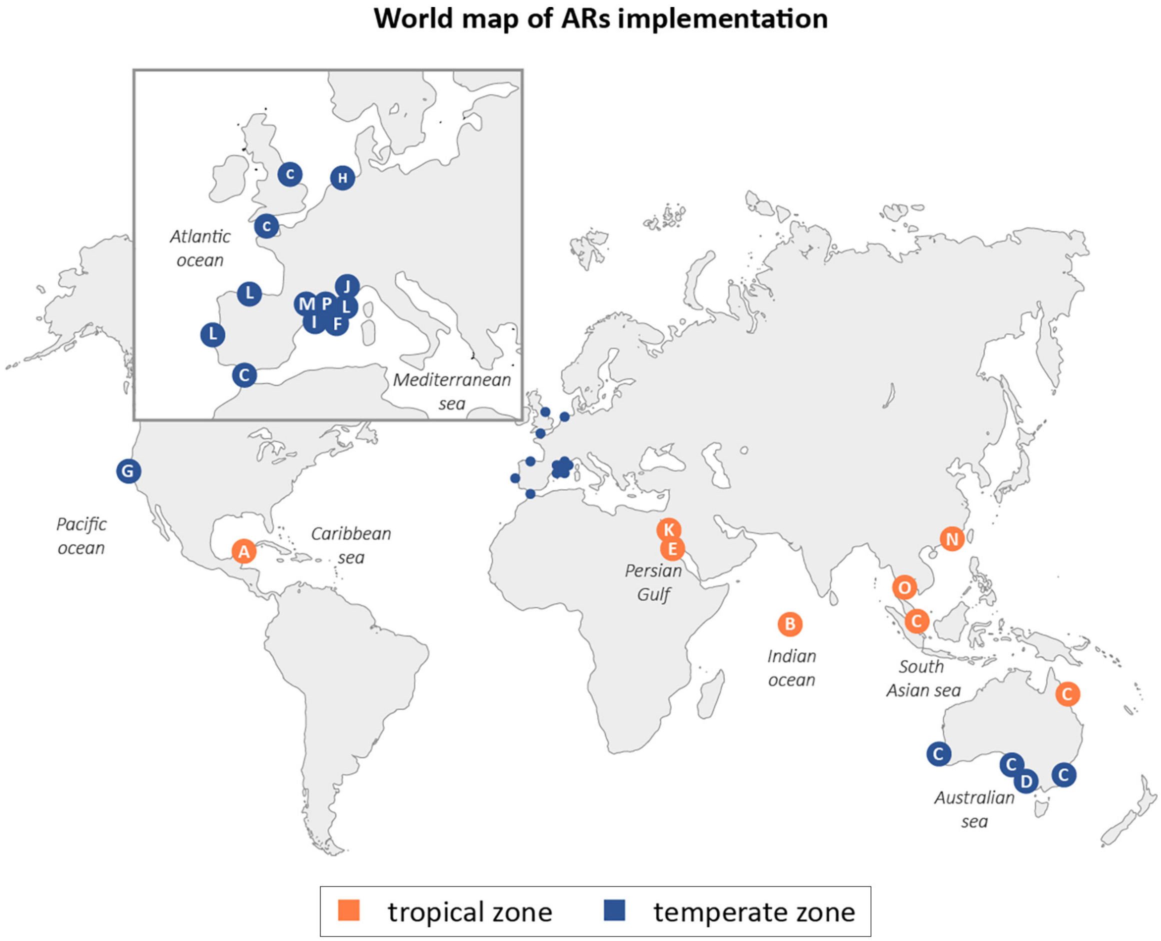


Source: Figure by authors

The 16 ARs examined were deployed in eight sea regions (Figure 21) distributed as following: 24% in the Mediterranean Sea; 24% in the Atlantic Sea; 20% in the Australian Sea; 12% in the South Asian Sea; 8% in the Persian Gulf; 8% in the Pacific Ocean; and 4% in the Indian Sea. South America and Africa regions did not present any ARs cases yet. The results demonstrated that they are mostly implemented in temperate regions (17 AR deployments) rather than in tropical regions (8 AR deployments).

The state of AM adoption in the world may be related to the implementation zones presented in this work. Reports from 2019 showed that the primary markets for AM technologies were

Figure 21 World map illustrates the implementation preferences of ARs placed in climate zones between temperate and tropical areas



Notes: (a) Hope 3D; (b) MARS; (c) Living Seawalls; (d) Wave Break; (e) Snapper Reef Unit; (f) Boskalis Reef; (g) Hanging Fish House; (h) 3D ReefVival; (i) X-Reef; (j) Biomimetic Reef; (k) X-Coral; (l) 3DPARE; (m) Recif'Lab L1. (n) 3D- Printed Reef Tiles; (o) InnovaReef; (p) Recif'Lab L2

Source: Figure by authors

dominated by North America (40%), followed by Europe (28%) and Asia (around 27%) of the market (Marak *et al.*, 2019).

Figure 22 shows the deployment bathymetry of every ARs under study. Most placement occurred between 15 and 26 m being implemented at greater depth preferably in temperate zones. On the opposite, in tropical zones, most cases were deployed between 6 and 12 m of depth. The established depths may define monitoring techniques to evaluate the effectiveness and productivity of ARs over time. Monitoring is a process of measuring, recording and comparing the achievements against a set of predefined target species (Kumar *et al.*, 2021). Due to the anchoring depth, all cases are accessible by scuba diving.

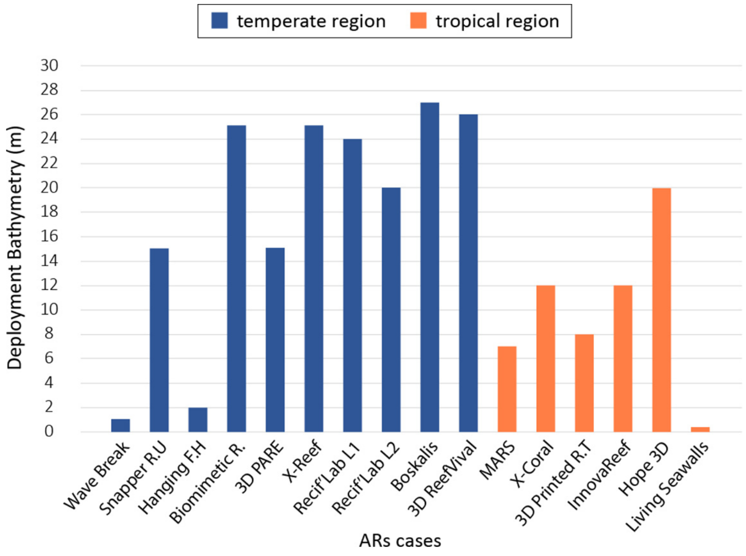
In terms of implementation methods, the results showed that 14 ARs were placed on the seabed, being the predominant approach; 1 AR used the floating method suspended by a buoy; and 1 AR case was affixed to existing marine walls.

There is a concern and tendency for AR placement in MPAs in the different countries of implementation. Protected areas provide additional habitat for biodiversity conservation, potentially providing management solutions for both natural reefs and ARS (Kirkbride-Smith *et al.*, 2016). Table 12 shows the ten AR projects identified within these protected areas.

4. Insights and outcomes

The research highlights a global commitment to achieving multiple ecological goals in the planning and manufacturing of ARs. All cases examined aligned with at least four ecological goals outlined in the PGUAR. These goals include enhancing biodiversity, providing new substrates for benthic settlement, mitigating habitat loss and offering shelter to marine life. Notably, this commitment goes beyond biological conservation and extends to incorporating design features that promote subaquatic tourism, mitigate waves and coastal erosion and enhance water quality by encouraging filtering organisms. This trend suggests that ARs are increasingly incorporating multiple

Figure 22 AR graph indicates the bathymetry deployment between temperate and tropical zones



Source: Figure by authors

Table 12 Identification of ARs placed in marine protected areas (MPA)

ARs	MPA location	The ecological goal of MPA	Reference
Hope 3D	Hol Chan Marine Reserve, Belize	Protect the coral reef community health and promote abundant fishery resources (including conch and lobster) associated with seagrass and mangrove habitats	Hol Chan (1987)
Boskalis Reef **X-Reef**	Calanques Park, France	Protect and preserve seagrass meadows, *Coralligenous* areas, fish, turtles,and cetaceans	Calanques Park (2012)
3DReefVival	Borkum Reef Ground, the Netherlands	Maintain and restore of habitat-type reefs	Kardinaal *et al.* (2020), Pogoda *et al.* (2020)
Biomimetic Reef **Recif'Lab L1** **Recif'Lab L2**	Cap' dAgde, France	Protect habitat diversity, including *Posidonia* meadows, rocky habitats, *Coralligenous*, sandy bottoms; conserve natural heritage, maintain integrated activities, control external factors and assess management effectiveness	Cap d'Agde (2020)
X-Coral	Eliat Coral Beach Nature Reserve, Israel	Protect and preserve coral reef ecosystems	Eilat Coral Beach Nature Reserve (1964)
3D Printed Reef Tiles	Hoi Ha Wan Marine Park, Hong Kong China	Protect coral communities and species diversity (mangroves and marine organisms)	Hoi Ha Wan (1996)
Wave Break	Clifton Springs Beach marine protected area in Victoria, Australia	Protect and improve biodiversity values	Thompson Berrill Landscape Design Pty Ltd (2008)

Source: Table by authors

ecological goals within a single structure, achieved through material selection and the implementation of complex design features facilitated by AM technologies.

PDM and BJ emerged as the most commonly used AM processes, showcasing adequate performance. They exhibit notable versatility to incorporate cementitious, ceramics and geopolymers materials and to facilitate the inclusion of residues or bio-receptive materials into the formulations. This adaptability enhances their suitability for the marine environment, target species and promotes a circular economy. Moreover, there is a prominent trend towards the exploration of new materials to replace Portland cement, such as pozzolan materials, aggregates derived from mineral and organic waste and bio-based resins. In this context, ceramic materials, with their non-toxic, pH-neutral properties, present a particularly advantageous option, offering sustainability benefits for the manufacturing of ARs.

Several cases were built through the AM process to create moulds for material casting. FFF proved to be cost-effective for carrying out this method. This approach allows the production of complex geometries not achievable through traditional methods, speeding up production and lowering costs. FFF also enables the casting of moulds near deployment zones, reducing transportation and logistics expenses. The PDM process is more cost-effective compared to BJ, considering both equipment and materials, though it does require laborious post-processing. When manufacturing takes place far from deployment areas, transportation costs become crucial. Using modular assembly methods, like Hope 3D, MARS, Living Seawalls, Hanging Fish House and 3D-Printed Reef Tiles, has proven to be cost-effective. Smaller modules provide better material control, customised textures, streamlined logistics and adaptability for larger areas as needed.

ARs through AM processes exhibit a trend toward incorporating structurally complex design features for ecological purposes. These include the integration of holes or tunnels for shelter zones; overhangs to mitigate sedimentation effects or to prevent the marine trawl nets effect; texture relief to enhance the area of the organism's colonisation; and platforms at varying levels to elevate the habitat structure from the seafloor. Innovative parametric methods, like lattice structures and algorithms of path generation for developing complex shapes, are becoming more prevalent in the PDM process. This technique allows to adjust the number of repeating patterns (internal architectural structure) or path directions to increase complexity, shape, reduce weight or strengthen the ARs. Half of the studied cases used these techniques. X-Coral combined lattice structures with the gravity-stimulated printing design technique (Berman *et al.*, 2023), which involves controlled gravity-assisted extrusion deposition. This combination of methods increased the acquired complexity, representing a novel strategy to achieve intricate and sophisticated shapes in AR developments.

Future advancements in AM technologies are expected to reduce costs, shorten printing times, decrease labour for post-processing, introduce new materials and control their dosage. AR projects have shown innovative solutions through AM technologies, but it is crucial to recognise that these projects are location specific. Standardising a universal solution may be challenging because of the diverse underwater conditions and habitat requirements. The primary advantage of AM resides in their capacity to create complex and customised geometries with a range of mortar materials suitable for marine ecosystems.

The effectiveness of ARs in achieving ecological goals has been evidenced by numerous cases that successfully aligned their design features with these objectives. The evaluation ranking presented both promise and challenge due to the urgent impact of climate change on marine ecosystems, the rapid evolution of AM technologies and materials and their accessibility. Furthermore, efforts are also being made to extend the benefits of AR implementations to countries that may currently lack access to these technologies or the resources needed for such applications.

5. Conclusions

This work critically examined the design, purposes and fabrication process of ARs through AM technologies for marine restoration and management. The review aims to offer valuable insights to researchers involved in the development of AM approaches for a wide range of marine applications, especially ARs. The conclusions extracted from the study are the following:

- Global commitment to ecological goals. The study identified primary and secondary ecological goals in the fabrication of ARs using AM methods, including biodiversity enhancement, substrate provision, habitat loss mitigation, marine life shelter, research/education support, habitat restoration, marine protected area creation, diving promotion, sensitive habitat protection and coastal erosion protection.
- Efficiency and versatility of AM technologies. ARs developed through AM processes are characterised by the potential to incorporate structural complexity to serve ecological functions. The versatility of AM allows customising the solution with morphology and texture variations adapted to different species and zones of implementation.
- Effectiveness and ecological impact of ARs. The ranking scores varied among AR projects, with considerations for ecological goals, biomimetic patterns, structural design features and environmental impact. 3D-Printed Reef Tiles, MARS, Living Seawalls, Wave Break and 3DPARE demonstrated the highest effectiveness score due to their design features and specific ecological goals.
- Trend towards sustainable materials. Innovative approaches, such as incorporating waste materials and advanced post-processing techniques, were observed in various AR cases. The review emphasised the importance of considering circular economy principles in AR manufacturing.
- Manufacturing impacts on logistics. The fabrication process directly affects logistics and associated costs. The modular assembly reef typology offers cost-effective implementation methods, particularly in areas with limited heavy machinery access.
- Future projections of AM in AR applications. The results provided insights for readers and researchers in marine ecology and/or AM fields, encouraging the need for continued innovation, sustainable environmental considerations, design features and material selection based on specific ecological goals and local conditions.

6. Glossary

Term	Definition
Design, materials and technology terminology	
Additive manufacturing (AM)	Technology that regroups all the manufacturing processes where three-dimensional objects are built by the deposition of material layer by layer
Biomimetics	Approach that mimics biological processes, models or pattern from nature to implement technical solutions
Subtractive manufacturing (SM)	Conventional manufacturing process that removes unnecessary materials to create the desired geometry, involving turning, milling, drilling, grinding, cutting and boring processes
Formative manufacturing (FM)	The conventional manufacturing process uses force, heat or pressure to mould materials into the desired shape. Examples of such processes include forging, casting, stamping, extrusion and injection moulding
Computer-aided design (CAD)	Digitally process to assist in the creation, modification, analysis or optimisation of two-dimensional or three-dimensional models of physical objects
Computer numerical control (CNC)	Automated control of machining tools to manage the movements and operations of machinery
Binder material	Substance that holds or draws other materials together to form a cohesive whole mechanically and chemically by adhesion or cohesion
Geopolymers	Inorganic polymeric materials obtained by mixing a dry solid (aluminosilicate) with an alkaline solution. An environmental alternative to traditional Portland cement by recycling waste materials and reducing environmental impact associated with the production or traditional cement
Alkaline material	Substances that have a pH level greater than 7, indicating that they are basic or alkaline in nature. The pH ranges from 0 to 14, with 7 being neutral, values below 7 being acidic and values above 7 being alkaline
Fused filament fabrication (FFF)	Additive manufacturing process that involves the layer-by-layer deposition of thermoplastic filament material to create three-dimensional object
Paste deposition modelling (PDM)	Additive manufacturing process that involves viscous paste-like materials to create three-dimensional objects, also known as paste extrusion
Kinematic design	In the context of AM, involves the movement control of the mechanical equipment, such as print bed and extruders
Lattice structures	Complex three-dimensional framework composed of interconnected geometric patterns, characterised by repeating unit cells or modules
Polylactic acid (PLA)	Biodegradable thermoplastic polymer derived from renewable resources, usually corn starch of sugarcane
Pozzolan materials	Group of materials, that when combined with calcium hydroxide in the presence of water, react chemically to form cementitious hydration products
Biological aspects terminology	
Biomass	Organic materials derived from living organisms, plants or animals, and their byproducts
Geogenic reef	Reef structure substrate derived from rocky stone
Biogenic reef	Reef structure substrate derived from carbonate deposition of habitat-forming organisms such as trees, oysters, wetland grasses and corals
Scleractinia corals	Commonly known as stony or hard coral, it plays a crucial role in the formation of reef habitats
Bleaching event	Phenomenon that occurs when coral polyps expel the symbiotic algae (zooxanthellae) living within their tissues. The expulsion of these algae results in coral death turning white, most known as bleaching event
Benthic communities	Group of marine organisms that inhabit on the bottom sediments of aquatic habitats
Sessile communities	Marine organisms that are attached to a substrate and do not have the ability to move around independently
Biota	All living organisms from a specific region or habitat
Bathymetry	Method of measurement and mapping underwater depths and the topography of the ocean floor
Anthropogenic facts	Phenomenon, substance or effect that arises from human activities, such as pollution, climate change, overfishing, habitat destruction, invasive species, etc.

Sources: Figure courtesy of Lange *et al.* (2020) and Reef Design Lab (2018)

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