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Discussion

# Emerging 3D technologies for future reformation of coral reefs: Enhancing biodiversity using biomimetic structures based on designs by nature

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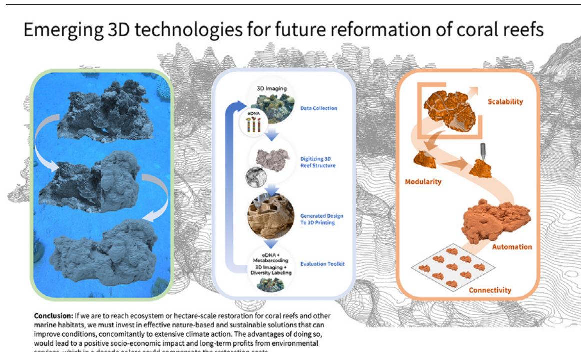
## HIGHLIGHTS

- Reef reformation often lacks sustainable, holistic, and scalable methods.
- 3D technology can customize artificial structures based on data from global reefs.
- 3D imaging acquires core characteristics of the reef from biodiversity to geometry.
- 3D printing offers tools to digitize 3D images into biomimetic structures.
- eDNA and 3D imaging can be used to evaluate goals and success of reef reformation.

## GRAPHICAL ABSTRACT

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## ABSTRACT

The rapid decline of vulnerable coral reefs has increased the necessity of exploring interdisciplinary methods for reef restoration. Examining how to upgrade these tools may uncover options to better support or increase biodiversity of coral reefs. As many of the issues facing reef restoration today deal with the scalability and effectiveness of restoration efforts, there is an urgency to invest in technology that can help reach ecosystem-scale. Here, we provide an overview on the evolution to current state of artificial reefs as a reef reformation tool and discuss a blueprint with which to guide the next generation of biomimetic artificial habitats for ecosystem support. Currently, existing artificial structures have difficulty replicating the 3D complexity of coral habitats and scaling them to larger areas can be problematic in terms of production and design. We introduce a novel customizable 3D interface for producing scalable, biomimetic artificial structures, utilizing real data collected from coral ecosystems. This interface employs 3D technologies, 3D imaging and 3D printing, to extract core reef characteristics, which can be translated and digitized into a 3D printed artificial reef. The advantages of 3D printing lie in providing customized tools by which to integrate the vital details of natural reefs, such as rugosity and complexity, into a sustainable manufacturing process. This methodology can offer economic solutions for developing both small and large-scale biomimetic structures for a variety of restoration situations, that closely resemble the coral reefs they intend to support.

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## 1. Introduction

Deep into the Anthropocene, coral reefs are among those of Earth's crucial habitats that are drastically changing, with a multitude of threats plaguing these marine ecosystems now more than ever. These threats occur on global scales including the effects of climate change, i.e., ocean acidification and cyclones that lead to coral bleaching events (Hughes et al., 2018); as well as on local scales, such as exploitative fishing and pollution from land-based sources (Weijerman et al., 2018). Coral ecosystems are extremely susceptible to these stressors (Gattuso et al., 2014) and may be affected by more than one concomitantly (Harborne et al., 2017). These critical habitats provide food, coastal protection, and revenue for millions of people (Woodhead et al., 2019); are a sink for approximately 29% of all $CO_2$ absorbed by the ocean (Jewett and Romanou, 2017); and host some of the highest species' diversity on the planet (Fisher et al., 2015).

Recent studies have stressed that the primary way to save impacted reefs is by engaging in urgent action to reduce global $CO_2$ emissions (Bellwood et al., 2019; Morrison et al., 2019). While this is a valid message, most measures aimed at tackling climate change on an international scale are often circumvented (Morrison et al., 2019), and require considerable time and major international cooperation (Ghedini et al., 2013; Hoegh-Guldberg et al., 2018). Although extensive priority should indeed be given to reducing climate change contributors, it is equally important to manage the local stressors affecting coral ecosystems (Abelson, 2020). Such action may increase reef resilience under future climate scenarios (Brown et al., 2013; Fox et al., 2019). However, there remains the belief that focusing efforts on coral restoration may steer necessary attention away from combatting climate change, or that even engaging in restoration is a lost cause if it cannot be projected onto ecosystem scale (Boström-Einarsson et al., 2020). Alternatively, the restoration of corals, preservation of reef biodiversity, and the recovery of critical reef species, should occur concurrently to the mitigation of climate and local stressors, to achieve the most favorable outcomes (Boström-Einarsson et al., 2020). In accordance with the UN Decade on Ecosystem Restoration, it is imperative to explore innovative technology that can upscale restoration, while supporting marine biodiversity (Anthony et al., 2017; Saunders et al., 2020).

At present, both active and reactive restoration, as well as proactive management govern reef conservation. Active and reactive restoration refers to intervention and assistance with the recovery process, such as coral gardening (Rinkevich, 2005) or macroalgal removal, while proactive management may refer to approaches enabling a natural rehabilitation or protective measures, such as Marine Protected Areas (MPAs) (Weijerman et al., 2018). Generally, a combination of these methods is applied to a given restoration situation. Nonetheless, coral reef restoration today mostly attempts to repair, or at best sustain remaining reefs and their associated biodiversity. Interdisciplinary methods involving new technologies are essential to facilitate reef functioning and maintenance of biodiversity, for preparing corals for the changes they are likely to encounter in the future. Currently, several innovative restoration studies are gaining attention, such as reseeding reefs with coral larvae (dela Cruz and Harrison, 2017), assisted evolution of corals (Chan et al., 2018), acoustically enriching degraded reefs (Gordon et al., 2019), and 3D printing for the creation of artificial habitats (Klinges, 2018).

One broadly used ecosystem repair strategy is that of the deployment of artificial reefs (ARs) on the ocean floor or suspended in the water column (Seaman, 2019). ARs are structures made from natural or fabricated materials that serve a wide range of purposes in aquatic environments (Seaman, 2019). Although they have many applications, such as protecting coastlines, promoting recovery, and supporting ecotourism, the most common use today is for fishery enhancement (Lima et al., 2019). Over the last few decades, increasing attention has been directed towards developing specific ARs to support coral ecosystems. The widespread loss of corals continues to leave behind diminished architectural complexity, which many reef species depend on for hunting, mating, and hiding (Alvarez-Filip et al., 2009). When structural complexity is reduced, the number of fundamental niches is simultaneously diminished, resulting in a decline in species diversity and richness (Loke et al., 2015). A key strategy by which to mitigate this problem is that of the addition of artificial structures to increase settlement space and complexity or to provide a platform for coral nurseries, which has been linked to the addition of biodiversity at recovering reefs (Loke et al., 2015).

However, most modular ARs today rarely replicate the 3D shape of marine ecosystems and often resemble structures close to, but not identical to the natural habitats they aim to rebuild. Recent studies advise that the steps necessary to improve these issues are to increase complexity and durability, to scale-up structures (Rogers et al., 2015), and to use sustainable materials for ARs (Boström-Einarsson et al., 2020). Designing artificial structures with various rugosity can play a determining role in species richness, habitat complexity, biodiversity and, by extension, the rate of recovery in a degraded area (Alvarez-Filip et al., 2009; Loke et al., 2015). Therefore, we believe that future AR production should focus on employing the data collected from each coral ecosystem (Boström-Einarsson et al., 2020), combined with innovations in AR assembly and design, to maximize their ability to achieve goals. A solution-based process that could encompass these needs is worthy of exploration, ultimately leading to the development of sustainable and complex ARs as an important reformation tool for coral ecosystems in the Anthropocene. Furthermore, as reef restoration is not a one-size-fits-all model, not every restoration method will be able to be applied universally. Recent papers have pointed out that the common reservations surrounding coral reef restoration are often concerning scalability, value, and effectiveness (Fox et al., 2019; Anthony et al., 2017; Kleypas et al., 2021). Perhaps, the ability to adapt a tool or method could lead to its customization for a variety of restoration applications.

Here, we address these concerns by providing a discussion on the evolution to current state of ARs as an ecosystem support tool and suggest how to tailor and upscale this tool for coral reef reformation in the current epoch. We reinforce this approach by supplying a workflow for construction to produce data-driven biomimetic designs inspired by natural reefs. We describe an interdisciplinary interface for the next generation of AR production with Industry 4.0 technology, 3D imaging and 3D printing (hereafter, 3DP). This interface utilizes data collected from coral ecosystems and 3D images to extract the core characteristics of a reef and its biodiversity, which is then translated into a digitized 3D printed AR. We further explain why this 3D interface offers a customizable solution to improve functioning and scalability of ARs that can be adapted to different reefs geographically. Furthering the development of ARs is necessary not only as a single tool, but also in combination with other restoration methods, such as increasing the effectiveness of coral transplants and nurseries (Boström-Einarsson et al., 2020). Although our main aim is for the improvement of ARs for coral reefs, our rationale could be relevant for fishery management, ecotourism, and coastal protection as well as for other marine ecosystems.

## 2. The evolution to current state of artificial reefs – where do we go from here?

Historically, deploying structures underwater has evolved over time from the Neolithic period, when boulders were submerged to attract fish (Lee et al., 2018), to modular structures engineered in the 21st century (Lima et al., 2019). The chronological development of ARs has typically been related to geography and application (Lima et al. 2019; Lee et al. 2018). ARs have evolved from existing as randomly placed objects or trash, deemed "materials of opportunity" (Bohnsack and Sutherland, 1985), to intentionally designed structures (Fig. 1). The concept of using fabricated materials arose in the 1980s (Bohnsack and Sutherland, 1985; McGurrin et al., 1989; Baine, 2001), and attitudes regarding sustainability changed (Bohnsack and Sutherland, 1985) to incorporate more eco-friendly materials (Seaman 2019; Thierry 1988; Spieler et al. 2001). Nonetheless, it should be noted that sinking military and civilian vehicles, planes, and ships as ARs, is still common practice around the world today, mainly for diving tourism.

The evolution of ARs was prompted not only by the realization that they should be constructed from sustainable and durable materials, but also by

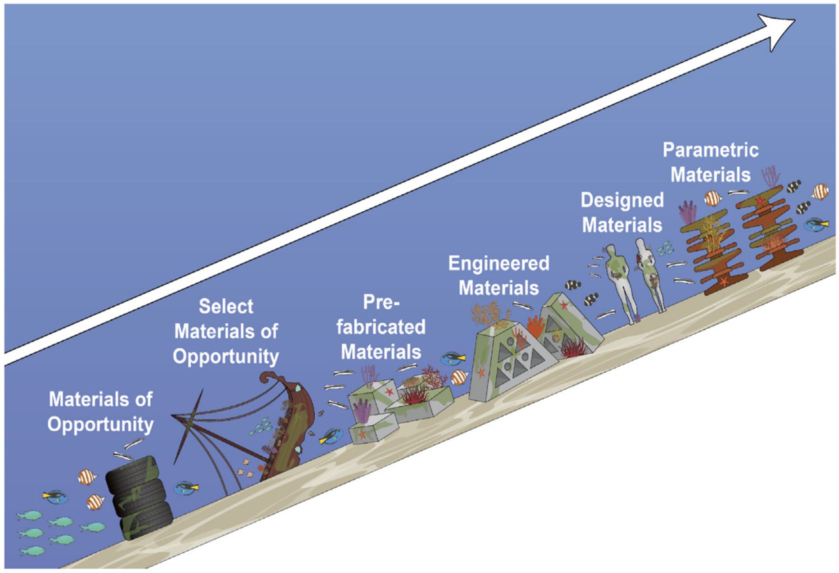



**Fig. 1.** The evolution of AR development for coral reef ecosystems. The shift in fabrication began with using discarded objects to create intentionally designed and eco-friendly structures. "Parametric materials" is a new term derived from parametric design, which refers to a dimension's ability to change shape and geometry, associated with the use of materials in 3DP (Jakšić et al., 2013).

the expansion of their application to include coastal protection, ecotourism, ecological studies, and restoration (Fig. 1). Specific studies on ARs for marine habitat enhancement were seldom published (Lima et al., 2019), however their surge in number has reflected the rapid decline of marine ecosystems in the 21st century (Lee et al., 2018). Lately, there has been an explosion of inventive studies aiming to improve AR function and support to benthic habitats (Klinges, 2018; Komyakova and Swearer, 2019; Riera, 2020; Riera et al., 2018; Ly et al., 2020; XtreeE, 2017; Ruhl and Dixson, 2019; Chamberland et al., 2017; Lange et al., 2020; Design Tech Lab, 2018; Goad, 2019; Crook, 2020; Gardiner, 2011). The main benefit of using ARs as a tool for supporting coral reefs include expanding the available substratum for benthic species (Abelson, 2006), adding structural complexity (Abelson, 2006), increasing recruitment and settlement of reef-building organisms (Abelson, 2006), attracting fish (Brickhill et al., 2005), and reducing diving pressures on natural reefs (Polak and Shashar, 2012). Nonetheless, there are drawbacks to using ARs, which may lead to the recruitment of non-native species, diversion of organisms or larvae from natural reefs (Bohnsack and Sutherland, 1985), potential negative effects on the ecosystem (Abelson, 2006), and attraction of species without production of new biomass (attraction versus production (Bohnsack and Sutherland, 1985; Brickhill et al., 2005)). Due to some of these issues the use of ARs is a widely debated topic regarding whether if, when, and how it should be applied to coral ecosystems. Until recently, ARs were not properly optimized to reflect the structural complexity of the natural habitats they intended to support (Komyakova and Swearer, 2019). Hence, we believe there is a clear need to examine current methodologies associated with AR production to improve their function, towards customizing scalable structures that are as close as possible to the geometry of natural coral reefs.

Previous AR literature has elucidated the importance of incorporating information collected from reef ecosystems, such as the recruitment and settlement of corals, fish, and other reef-inhabiting organisms to maximize AR effectiveness (Whalan et al., 2015). When seeking to promote biodiversity recruitment through ARs, it is crucial to know which abiotic and biotic factors can induce the settlement of reef species. Understanding how to utilize these factors, from surface topography (Whalan et al., 2015) to chemical cues (Randall et al., 2020), can promote the settlement and survivorship of marine organisms and is critical for AR development, functioning, and preventing deleterious changes in reef environments (McDonald et al., 2016). It is important to note that other factors such as nutrient cycles, location, duration of deployment, and environmental and anthropogenic disturbances (Fox et al., 2019; Komyakova and Swearer, 2019; McDonald et al., 2016; Burt et al., 2009; Tokeshi and Arakaki, 2012), can affect the efficiency of ARs beyond aspects related to the development process. Here, we will focus on those characteristics that we believe are particularly important when developing ARs for coral reef environments, such as structural complexity, rugosity and topography, biomimetic design, and shape.

The reduction of biodiversity in marine habitats is often linked to the reduction of microhabitats such as crevices and pits, leading to a lack of structural complexity (Alvarez-Filip et al., 2009). Artificial structures engineered with high complexity and structural niches to accommodate different sizes of organisms, often contribute most to increasing and maintaining biodiversity at the recovering reefs (Loke et al., 2015; Tokeshi and Arakaki, 2012; Torres-Pulliza et al., 2020; Dafforn et al., 2015). ARs that mimic the topography of natural reefs may help to reduce colonization by non-native species (Dafforn et al., 2015), providing a potential advantage to rare and endangered species (Polak, 2012). For example, it was found that scleractinian corals, the major reef-building organisms, generally favored abrasive surfaces that offered shelter, while some soft corals are attracted to the edges of structures and organic materials (Benayahu and Loya, 1987). The findings suggest that the material composition of a structure can stimulate coral metamorphosis (Randall et al., 2020): ceramics, such as terracotta clay, are commonly used in artificial scientific structures because it is favored by coralline algae, which is known to significantly increase the settlement of corals and other benthic organisms (Randall et al., 2020).

The structure and design of an AR developed for coral ecosystem enhancement can determine its overall performance, such as its ability to increase species richness and biomass (Sherman et al., 2002; Charbonnel et al., 2002; Gratwicke and Speight, 2005). The structural complexity of a reef has been correlated with its biodiversity of fish and invertebrates (Gardiner, 2011; Dafforn et al., 2015; Gratwicke and Speight, 2005). Complexity incorporates several elements, from the micro-details embedded into a structure, to its physical shape and rugosity. For instance, ARs that are more complex increase the settlement of coral larvae on both macro- and micro-scales (Yanovski and Abelson, 2019). Komyakova and Swearer found that AR design was a contributing element to the associated biodiversity, regardless of where the AR was deployed (Komyakova and Swearer, 2019). AR designs should be tailored to reflect natural reefs as well as native species at the intended deployment sites (Perkol-Finkel and Benayahu, 2009). Perkol-Finkel and Benayahu showed that benthic communities on an AR had become similar to those of the native reef over a few decades, while also noting that this outcome could be due to the AR's ability to replicate the features of the natural reef habitat (Perkol-Finkel and Benayahu, 2009).

Designs for AR structures are often not optimized for ecological functioning (Loke et al., 2015; Kovalenko et al., 2012), as they can be flat and homogenous in relation to the intricate ecosystems they aim to support. If the main goal is to assist certain ecological processes (e.g., increasing or maintaining biodiversity), then ARs should be developed according to baseline or current data, derived from the coral reef in question, and used to inform future fabrication. We advocate that once AR goal(s) have been defined, all other workflow aspects, such as establishing a baseline, design, production, and evaluation, should follow suit and thereby, prepare ARs for optimal performance. Today, the consensus is that coral reefs are facing serious threats, from environmental to anthropogenic, with 70–90% of corals potentially disappearing within the next 30 years (IM et al., 2019). Such a scenario would be highly detrimental, as these reefs contribute an estimated $375 billion to the global economy (IM et al., 2019). The transition to scaling-up reef restoration to hectare-scale, will require embracing interdisciplinary technology and allowing time for optimization, which could very well lead to an improvement in restoration effectiveness (Saunders et al., 2020). Further highlighting a fundamental need for AR production derived from a data-driven approach towards bio-designs, which have the scalable mass-production abilities to support reef reformation.

## 3. Blueprint for customization of artificial reefs

### *3.1. 3D printing (3DP) for sustainable design, scalability, and mass-production*

In the 4th Industrial Revolution (Industry 4.0), technology is interlacing with science at an unprecedented pace, and understanding how to harness this crossover could create opportunities to develop new enhancement tools for coral reefs. One recent advancement incorporates the use of additive manufacturing (AM) technology to create ARs (Mohammed, 2016). AM is an industry term encompassing all methods of additive technologies, such as 3DP (Guo and Leu, 2013). 3DP is a computer-controlled process for creating volumetric objects that are constructed by depositing layers of material (Ngo et al., 2018). This process is already being used to promote biodiversity on marine infrastructures, such as seawalls and coastal defense structures (Goad, 2019). The knowledge gained from these projects has led to the development of 3D printed habitats, oyster reefs (Goad, 2019), and modular ARs (Klinges, 2018). Optimizing ARs is important for maximizing their ecological impact as a scalable and versatile tool for benthic marine ecosystems.

We suggest that to improve the next generation of ARs (Komyakova and Swearer, 2019) it is important to know how to integrate 3DP with other technologies. This may include leveraging advancements in data collection such as molecular biology (i.e., environmental DNA (eDNA)) and 3D imaging to evaluate the coral ecosystem and provide a base for AR design. 3DP for artificial structures has been drawing increasing attention, with several projects aimed at adding structural complexity and recruiting biodiversity to marine ecosystems (Lange et al., 2020; Design Tech Lab, 2018; Zavoleas et al., 2020; Evans et al., 2021). As 3DP has only recently been adapted for coral reef environments (Gardiner, 2011), there is still a learning curve to understanding the best practices of this technology for developing ARs. Conceivably, the next advancement in the field of 3DP ARs will be that of adjusting mass-customization (MC) abilities, as an emerging approach to enhancing and complementing AM towards personalized industrialization (Daaboul et al., 2011). MC refers to designing and producing customized items with the same effectiveness and cost as mass-production (Daaboul et al., 2011). Through parametric computer-aided design (CAD) platforms such as Rhinoceros© and Grasshopper©, it is possible to rapidly customize attributes of the design, and thereby integrate greater variety and modularity into 3D printed objects (Zastrow, 2020). Utilizing 3DP offers the ability to modify, reprint, and refine complex designs in an agile process that avoids excess waste, as opposed to other conventional and fixed manufacturing processes, such as molds. 3DP could have an important role in sustainable fabrication of ARs in terms of waste, material consumption, and environmental pollution (Khosravani and Reinicke, 2020). 3DP, in general, is already projected to reduce several costs associated with manufacturing as well as global $CO_2$ emissions (Gebler et al., 2014). Since certain AM processes are inherently sustainable based on reusing, recycling, and biological materials to limit negative impacts on the environment (Khosravani and Reinicke, 2020).

Today, 3D printers can print massive industrial structures, including bridges and houses, at timely and cost-effective rates (Zastrow, 2020). Therefore, the advantages of 3DP combined with MC could exceed previous AR fabrication processes, by providing customization tools for enhancing the structural features and designs of ARs. More specifically, 3DP may offer potential answers to some of the persistent problems surrounding AR functioning and development (Spieler et al., 2001; Komyakova and Swearer, 2019). As 3DP is a computer-driven process, it is possible to create scalable ARs that can mimic the 3D reef structure, topography, and morphology (Fig. 2). Commonly, ARs are often pieced together from various inexpensive, prefabricated, non-natural materials, such as concrete and steel (Gardiner, 2011), leading to designs that are often square, block-like, round, or even constructed into shapes that barely resemble a coral reef. Most commercial ARs, like Reef Balls© (Barber and Barber, 1998), use manufacturing techniques that are readily available for mass-producing replicates, which limits their inclusion of heterogeneous features (Gardiner, 2011).

The three most common 3DP methods of artificial marine structures are binder jetting, paste-based extrusion, and fused deposition modeling (FDM) (Fig. 2). These modalities are mainly used because of their ability to swiftly execute diverse shapes of 3D objects according to the printers' specific build volume. Depending on the chosen printer and method printing will vary in size, speed, and available materials; but, more importantly, the type of additive technology will affect the ultimate form, function, and shape of the AR produced. Each of the printing technologies has built-in guidelines (Redwood et al., 2017), which help to control and define the AR to achieve the most effective results. Binder jetting technology is known for producing objects with accurate shapes and details such as crevices, hangovers, or voids (Shahrubudin et al., 2019; Gibson et al., 2021). FDM is one of the most known and affordable 3DP set-ups and is compatible with thermoplastic polymers and bioplastics (Tarazi et al., 2019); however, plastics can be toxic in marine environments over time (Weiss et al., 2012). Although paste-based extrusion may not be able to print objects with the same precision as binder jetting or FDM, its advantages allow the printing of small to large-scale complex structures with short production times at low costs (Tarazi et al., 2019; Ruscitti et al., 2020).

Current examples of AR structures created from all three printing types demonstrate a variety of designs, materials, and complexities (Fig. 2). Binder jetting technology was used for SECORE's seeding units, which have been found to increase settlement of coral larvae at various global reefs (Chamberland et al., 2017). The BOSK AR module was developed for habitat restoration and designed to include different microhabitats to function for biogenic reef species (Riera, 2020) (Fig. 2). FDM printing technology is often used in projects to recreate 3D replicas of corals (Ruhl and Dixson, 2019; Tarazi et al., 2019; Pérez-Pagán and Mercado-Molina, 2018). Many of these studies found no significant differences between 3D bioplastic corals and real coral skeletons for recruiting reef fish and coral larvae and found that reef organisms preferred structures with a greater degree of complexity (Ruhl and Dixson, 2019; Pérez-Pagán and Mercado-Molina, 2018). The MARS structure used FDM to create the individual arms of the AR, using a process called slip casting to make molds that were later filled with marine concrete and reinforced steel (Klinges, 2018; Goad, 2019) (Fig. 2). Paste-based extrusion is frequently used for developing ARs with large volumes, often intended for enhancing structural complexity and biodiversity in marine environments, such as 3DPARE modules designed as "low-impact" structures (Ly et al., 2020) and Rexcor reef (XtreeE, 2017) (Fig. 2). Both 3D printed ceramic tiles (Lange et al., 2020) and xCoral units (Design Tech Lab, 2018) were created from ceramic terracotta to biomimetically replicate coral morphologies.

Coral reefs with a high variety of species assemblages and diversity generally display greater bioconstruction patterns (Alvarez-Filip et al., 2009; Kovalenko et al., 2012). While the complexity of natural reef structures is

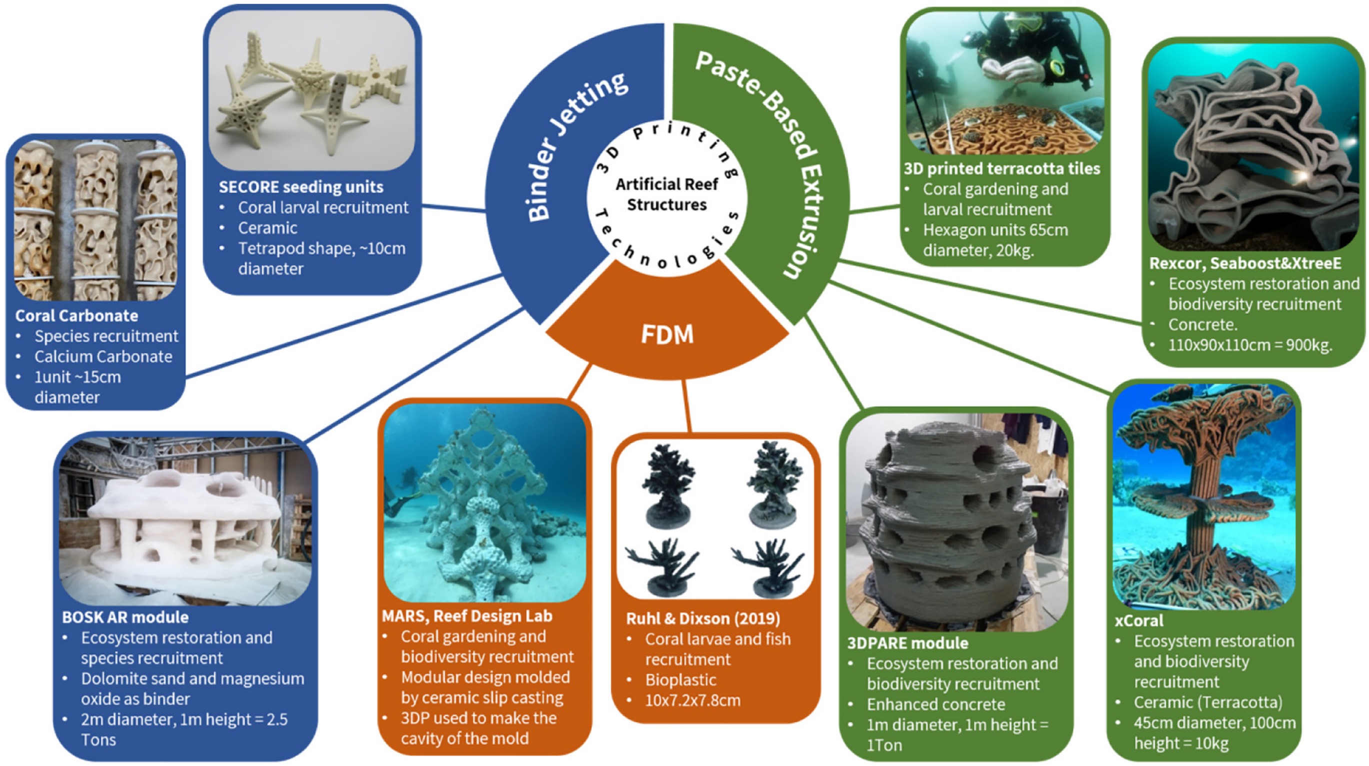



**Fig. 2.** Recent AR structures fabricated with 3DP for use as biodiversity or structural tools in reef ecosystems. The structures represent alternative approaches to manufacturing highly complex objects according to each 3DP technology. Each printing technology offers different production methods, materials, and precision of design, sizing, shape, and structural stability. All structures either have been used or are currently being used in experiments.

created over time, 3DP offers a customization process able to rapidly build up this complexity to produce bio-inspired artificial structures. 3DP can produce intricate designs without compromising on surface area — a challenge presented in earlier AR construction (Kovalenko et al., 2012), and essential for increasing biodiversity and providing settlement space. MC and 3DP offer a sustainable streamlined process to scale-up ARs and restoration efforts, by producing a variety of either all-purpose or fit-for-purpose structures, sizes, and designs, from a range of eco-friendly materials. Additionally, 3DP can be combined with other digital technologies such as 3D imaging to produce biomimetic structures that are derived from the natural topography and geometry of coral reefs. These essential advancements in the field of ARs, have the potential to upscale this restoration tool by expanding its functional ability to support coral ecosystems.

### *3.2. 3D imaging as a data-driven optimization tool*

Our perception is based on the notion that AR design should resemble natural reefs to the highest degree possible, maximizing restoration efforts both ecologically and aesthetically. Coral reefs should be thus mapped in a manner that best describes their 3D features and community structure, across several spatial scales (cm to km). Diver-based photogrammetry has been established over the past decade as a repeatable method for benthic 3D mapping (Burns et al., 2015; Edwards et al., 2017; Ferrari et al., 2017; Yuval et al., 2021). This technology enables the production of highly detailed 3D models of the substrate and detection of the sessile organisms that inhabit the reef (Fig. 3A). Thus, conducting photogrammetric surveys in areas, which are designated for reef replenishment using ARs is highly beneficial, as it identifies which reef structures harbor the largest number of species as well as depicting their numerical composition (diversity) within the reef structure (Fig. 3).

A reef can be described by different geometrical metrics, such as rugosity (the ratio of a chain and tape), or surface complexity (the ratio of volume to surface area). Previously, the measure of rugosity has been shown to correlate with biodiversity and topographical complexity (Friedman et al., 2012). However, it is well known that rugosity by itself cannot encompass all aspects of the 3D structure and new measures have been suggested for replacing it (Torres-Pulliza et al., 2020). Moreover, in our opinion, scalar measures cannot in themselves characterize coral reefs precisely enough for optimal biomimicry. For example, the spatial arrangement of topographical features (i.e., crevices, overhangs, caverns, etc.) also influences the reef's potential to shelter species further up the food chain, such as herbivorous fish (Hylkema et al., 2020). An AR may therefore include various sizes of holes and cavities to provide hiding and feeding grounds, but this specific design may not work as well to increase the settlement of small benthic organisms, because it may lack the surface area and space necessary for supporting new life. In conclusion, an AR should include a combination of micro- and macro-topographical features that allow it to mimic the 3D structure of a real reef enough to be effective. Moreover, 3D imaging (photogrammetry) paves the way for fully autonomous monitoring. It is a scalable technology that can be utilized in rapid assessments of reef scapes, thus enabling the identification of the underlying mechanisms of reef degradation ahead of time rather than post-mortem. A prompt response to a degradation scenario is an important aspect of reef restoration, by employing solutions prior to natural catastrophes and phase shifts.

Conceivably, 3D imaging of coral reefs offers a way to rely on nature to provide the foundational structure for creating ARs. With CAD design platforms (i.e., Rhinoceros© and Grasshopper©), there can often be a gap between replicating a design created by nature vs. a biomimetic or bio-inspired design in 3DP. Incorporating 3D images provides a natural basis for constructing an AR that can be customized to any type of reef geographically. Since many institutions are moving towards 3D imaging for data acquisition, 3D images of global coral reefs are readily available and can be freely downloaded as models that can be translated to 3DP using CAD software. Moreover, the plethora of accessible 3D models should be further analyzed geometrically using advanced data-analysis tools, to extract the general features and characteristics that will lead to a successful AR. This can be done per location, depth, etc., to further customize and refine the biomimetic design. Foreseeably, 3D technology such as 3D imaging and

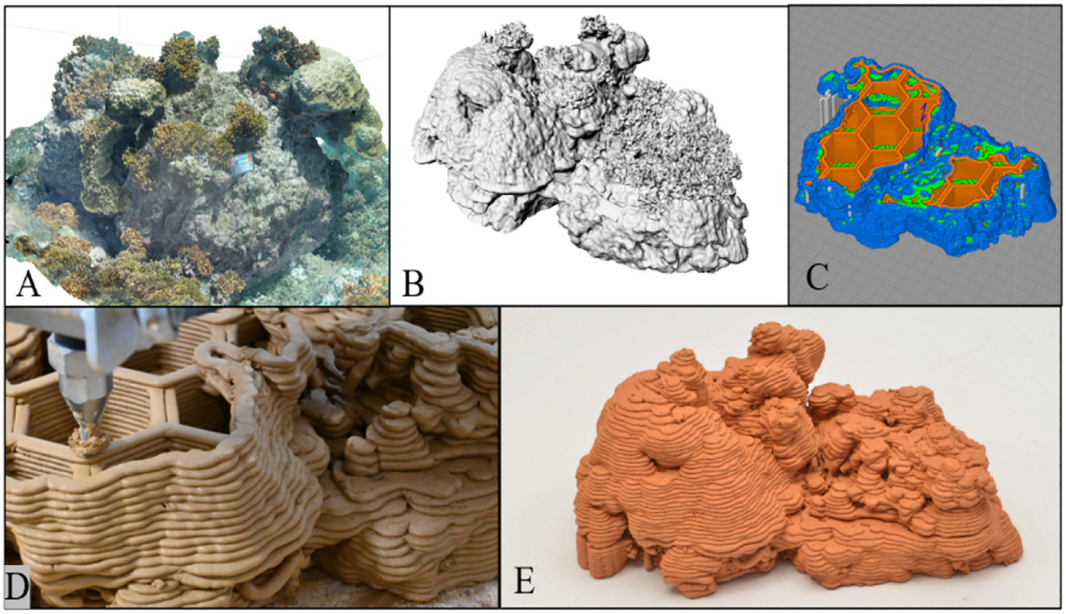



**Fig. 3.** Our 3D interface of generated design to 3DP. A) Image of a 3D model of a 3 $m^3$ reef patch. B) The scanned 3D model imported into the Rhinoceros© design environment. C) A section showing the layering of the model in a slicer (Simplify 3D V.4), exhibiting how the [terracotta] clay structure will be printed. D) The reef patch being printed on a 1:5 scale by a WASP 3MT paste-based extrusion 3D printer. E) The completed 3D printed AR.

3DP will meet in the middle to bridge design gaps (Rossi et al., 2021). Potentially leading to software or plug-ins for designing artificial structures that consolidate algorithms based on the formation of a coral reef structure (Sun et al., 2017) (i.e., complexity and geometry) and the types of biodiversity it will ultimately support (Rossi et al., 2021); subsequently, utilizing a holistic and nature-based algorithm to design the AR.

## 4. Suggested restoration solutions with 3D technologies: value and benefits

Previous studies have emphasized that when ARs incorporate attributes of natural reefs (Komyakova and Swearer, 2019; Riera, 2020), they can attract similar community of species representative of neighboring natural reefs (Perkol-Finkel and Benayahu, 2009), which has been shown to promote biodiversity (Dafforn et al., 2015; Gratwicke and Speight, 2005) and enhance growth and recovery of coral species (Clements and Hay, 2019). 3DP ARs may offer benefits over traditional structures that could help rectify previously mentioned drawbacks in Section 2. This could further minimize deleterious effects on the ecosystem, attract new biomass, and facilitate the settlement of local and native species, as our proposed 3D interface can utilize the data of the coral ecosystems they intend to support, or from reefs featuring high biodiversity to sustainably customize 3D printed reefs. ARs could serve several functions for reef managers, not only to add substrate and complexity, but also as individual ecosystems to fertilize degraded reefs with microbes and nutrients, or as coral nurseries that could be specially designed for attaching coral transplants or fragments. A recent review demonstrated that ARs that included coral transplants saw an increased survival rate of 66% (Boström-Einarsson et al., 2020), which could be due to many processes, for instance, the AR providing a substratum for an ecobiome of essential nutrients and organisms to mutually benefit the corals (Marangon et al., 2021). As 3D printed ARs can be intricately customized with assorted structural niches, it could support a variety of diverse and fundamental organisms, attract reef fish that may lead to macroalgal suppression, and other associated benefits influencing coral health. Although our 3D biomimetic interface may not suit every restoration situation, we suggest the following ways it could be integrated: as stepping-stones to connect healthy and degraded reefs, coral nursery platforms, in sand patches to create a sink for new life, at degraded reefs lacking structural complexity, and as moveable structures that can transfer essential species and nutrients from a healthy to degraded reef. In instances where the target reef in need has a significant reduction of complexity and diversity, we suggest using 3D models from neighboring healthy reefs with high 3D complexity and biodiversity, from the same endemic population and geographic region. This can be done by pinpointing the most important reef characteristics and parameters necessary for maintaining as much diversity as possible, through data collected (i.e., eDNA and 3D images) from the reef where the 3D model was taken (Yuval et al., 2021). 3D printed ARs could be further customized to the specific needs of the reef through CAD software.

Until recent advancements in 3D technologies, previous ARs manually attempted to incorporate ecosystem data into the development process. Digital design tools and parametric software now enable the conversion of real-time information extracted from coral reefs to produce data-driven biomimetic designs. However, when the underlying causes of reef degradation have yet to be determined, the assessment of the ecosystem health, biodiversity, and environmental conditions could help infer restoration-specific needs, and later, evaluate success. These surveys can serve as a baseline of the ecosystem state pre-restoration and the data collected could also be applied to customize the restoration method to the ecosystem (Fig. 4). As described in Section 3.2, 3D imaging and photomosaics are becoming key tools for coral reef mapping and for capturing changes on multiple scales at high resolution (Yuval et al., 2021; Friedman et al., 2012). In addition, the core reef characteristics can be extracted from 3D models to provide the foundation of the AR design. Baseline data and surveys to understand the fundamental issues affecting a coral reef could conjointly be applied to mitigate challenges indicated by past studies on how to evaluate if ARs were successful in meeting their goals (Spieler et al., 2001; Komyakova and Swearer, 2019) (Fig. 4). Improving and standardizing surveys by which to assess these objectives could offer the means to achieve more conclusive results for AR studies and restoration.

As 3D printed ARs are designed with detailed complexities that may make traditional monitoring difficult to implement, a combination of molecular (i.e., eDNA) and imaging methods could provide essential biodiversity information, such as on rare or cryptic species (Stat et al., 2017) that may not be revealed by traditional biodiversity surveys. eDNA is DNA collected from air, water, sediment, biofilm, or organismal samples from the environment, which can be combined with metabarcoding to mass-amplify information regarding species biodiversity, richness, and

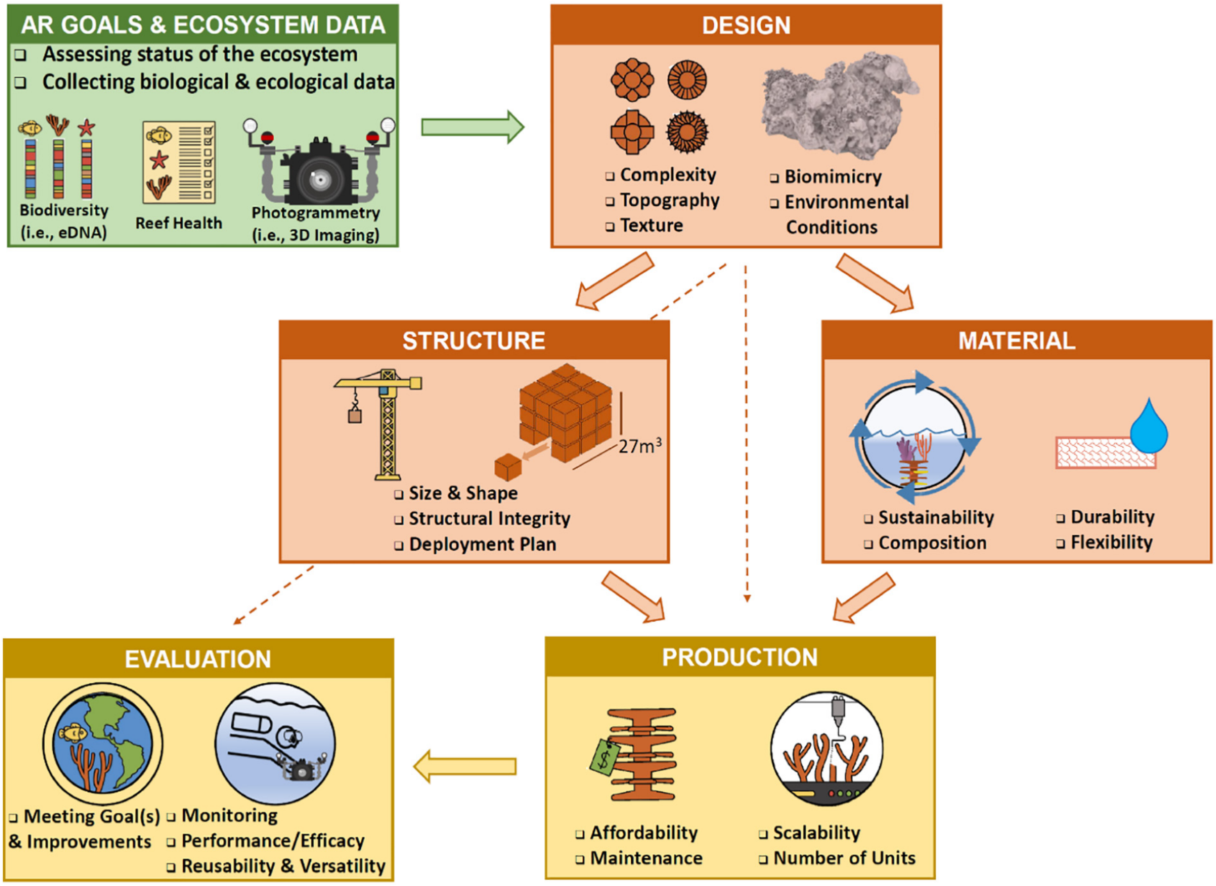
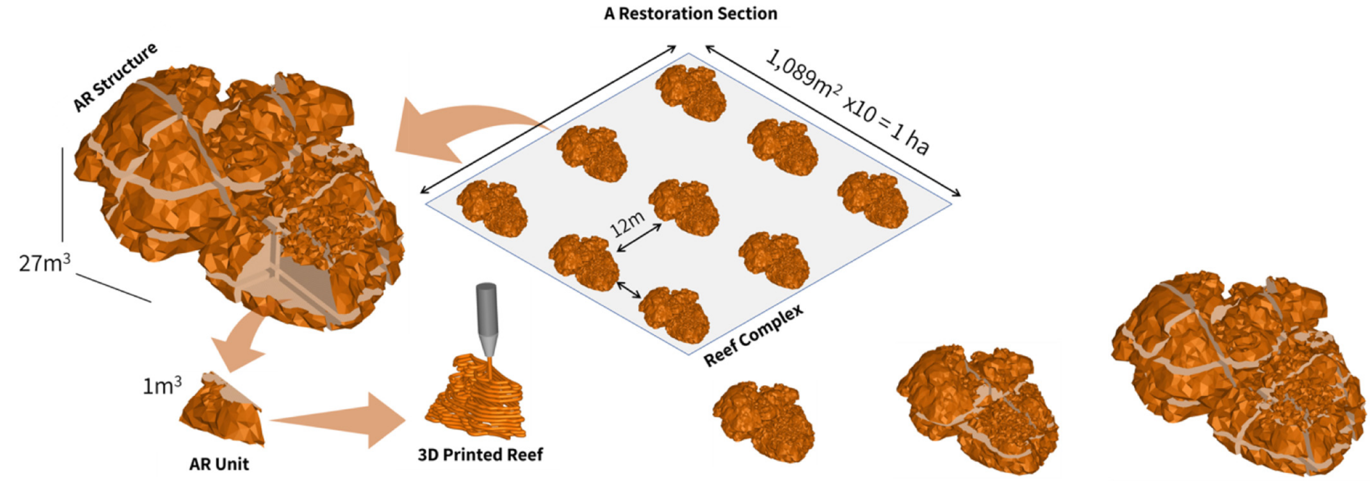



**Fig. 4.** Suggested data-driven blueprint. Towards optimization and automation of AR design, production, evaluation, and management.

abundance (Stat et al., 2017). eDNA and metabarcoding are already being adopted for monitoring coral reefs (Leray and Knowlton, 2015). Benthic structures were used to provide an overview of reef biodiversity (Leray and Knowlton, 2015) indicating the pivotal potential of eDNA and metabarcoding as an evaluation tool for ARs and reef restoration. For example, features or removable appendages could be 3D printed as part of AR designs, which could be used for organismal eDNA surveys alongside collecting water samples, without disturbing the restoration process. As the information extracted from eDNA is broadly expansive, it can be utilized to predict biodiversity outcomes of the 3D printed AR based on the 3D imaged reef. Furthermore, eDNA data can help to understand what characteristics of the 3D modeled reef are related to the diversity of organisms that inhabit it, which can be used to guide the fabrication of the AR. Cryptic organisms on coral reefs comprise most of the reef diversity and are usually overlooked, eDNA provides information on the cryptic invertebrates that have settled regardless of the life stage (e.g., newly settled coral polyps) (Stat et al., 2017), which could be advantageous for both short- and long-term studies as an evaluation metric. eDNA is a useful tool to observe these hard to identify communities and to understand which species benefit most from the AR structure. This information could be collected to understand the community composition, abundance, and richness, available through eDNA analysis, either directly from biomass samples from 3D printed ARs or from the surrounding water. Though eDNA and metabarcoding are decisive tools, they are still limited by the information of biodiversity databases and taxonomic assignments (West et al., 2021). Therefore, coupling these molecular tools with 3D imaging and traditional monitoring methods, can help ensure the most conclusive results. Establishing an efficient plan using eDNA and 3D imaging as an evaluation metric, could help to bridge the gap between unsuccessful and successful AR studies, and inform future development. However, if ARs are deemed ineffective following evaluation, it might be necessary to remove them to prevent potential deleterious environmental changes.

Data collected from coral reefs, using eDNA and 3D imaging, can reinforce their resilience through establishing baselines, monitoring, and evaluation of restoration activities. Combining these data-acquisition tools with 3DP offers a holistic approach to manufacturing biomimetic ARs that are tailor-made to any coral reef in any geographic region (Fig. 4). Eventually leading to an entirely data-driven interface utilizing parametric design software and machine-learning tools to curate an algorithm for customizing ARs, according to the specific characteristics of the coral reef, such as reef structure/type, biodiversity, depth, coral morphology, etc. Moreover, the algorithm could automate the optimization of AR designs according to the data it is supplied from eDNA, 3D imaging, and other monitoring surveys. This methodology would make it possible to determine the precise design parameters needed to construct an AR, provide a baseline for the expected biodiversity that could accumulate on 3D printed ARs, and ensure no excess waste in the manufacturing process. Although there is vast potential, this process is still in its infancy, with advanced data analysis methods needing to be developed to extract the complexity parameters of coral ecosystems to create large-scale ARs.

Marine restoration is a relatively young field compared to terrestrial restoration. Therefore, we must work towards addressing its most pressing challenges: the development of sustainable large-scale (Fig. 5) and long-term projects that can provide key social and economic benefits (Saunders et al., 2020). When marine restoration projects managed to meet these requirements, they were able to achieve restoration goals. For example, in Indonesia and Florida, long-standing community and regional reef restoration projects successfully regenerated large areas of coral and facilitated biodiversity (Saunders et al., 2020). The MC and mass-production abilities of 3D technology combined with data-acquiring tools could




| | 1m³ cluster | 8m³ cluster | 27m³ cluster |
|---|---|---|---|
| AR volume Per 1/10 hectares | 81m³ | 162m³ | 243m³ |
| Production capacity (1 year) | 1.2 Hectares | 0.6 Hectares | 0.4 Hectares |
| Price (Euro) (not including installation) | 55K | 110K | 170K |

**Fig. 5.** Scalability and estimated cost of ARs to hectare-scale with integrated 3D interface. ARs can be scaled using 3D images to any size and structural shape depending on the desired parameters and feasibility of the printing method. We recommend ARs to be deployed according to the spatial distribution of scleractinian coral (main reef-builders) assemblages at sites. The table represents an example cost analysis based on AR volume per 0.1 ha, production capacity, and price (not including installation) (10,000 $m^2$ = 1 ha). This set-up is based on the use of a single industrial paste-based extrusion 3D printer with an average build volume of 1 $m^3$.

provide opportunities for all types of restoration projects, from small to hectare-scale (Fig. 5). Coastal communities relying upon their reefs for resources, coastal protection, and livelihoods, could operate simplified 3DP reef reformation projects according to their needs, available resources, and external assistance. For small-scale reefs, inexpensive desktop 3D printers could be used requiring less maintenance, 3D printers could be shipped via air or sea, or 3D printers and small workshops could be installed in freight containers. The know-how to manage 3D printers could be disseminated to local communities to provide upkeep and maintenance of machines depending on their complexity. Communities could utilize 3D images of their reefs to 3D print structures, use existing models, choose design characteristics tailored to local reefs, or even extract original models using simple submersible cameras and free 3D imaging software. Materials could be sourced from natural coral rubble ground into calcium carbonate powder (used in binder jetting 3DP (Crook, 2020); Fig. 2). One example of sustainable 3DP is from a project in the Solomon Islands, where they sourced recycled waste material and used a solar charging battery system (e.g., EcoPrinting) to offset their carbon footprint and minimize energy use (Gebler et al., 2014; Nadagouda et al., 2020).

Depending on the desired application, 3DP technology varies in cost from desktop to industrial printers. Increasing the use of 3DP for different fields, such as marine structures and restoration may help to reduce prices or lead to the development of printers specifically for this purpose. Purchasing professional ($3-10K USD) to industrial machines ($10-300K USD), capable of large-scale production, could be a worthwhile investment as many are built to last for decades, if properly maintained. If a reef reformation project uses only one industrial, paste-based extrusion printer that is compatible with a variety of ceramics (i.e., terracotta clay), and has an average build volume of 1 $m^3$, the production capacity within a year could produce a range of small (1 $m^3$) to large-scale ($\leq$27 $m^3$) ARs at hectare-scale (see Figs. 3E and 5). Additionally, printing high volumetric ceramic ARs with complex geometries will result in less material consumption per cubic meter due to reduced structural overload when the AR is submerged underwater. The weight of an average cubic meter (1 $m^3$) of printed ceramic (see Fig. 5), with an estimated density of 3.8 $\times$ 103 kg/$m^3$, thickness of 2 cm, and layering height of 7 mm is approximately 1 ton, as clay has about 20% humidity. If terracotta clay costs roughly $0.50 (USD)/kg, then the material needed for a 1 $m^3$ AR (see Fig. 5) would cost approximately $600 USD. Producing ARs from ceramic is a relatively sustainable process due to the material's compressive strength and long-lasting anticorrosive properties, which allows for a stable structural design. Also, glazing is not necessary as the clay is only fired once at low temperatures to increase porosity underwater. However, this is just an example of one type of 3DP setup for AR production. Actual prices, sizes, and manufacturing times will vary depending on the printer type, number of printers, build volume, materials, and size of units or ARs.

It is important to clarify that choosing which type of 3DP technology is right for ARs does not have to be based on whether to buy a 3D printer; but, rather, on adopting this technology for up-scaling AR production and support to coral reefs. As noted above, depending on the budget, a less expensive smaller 3D printer could be an ideal choice, as it could print stackable units (rather than one large unit) to create different AR volumes (Fig. 5). This idea was promoted for a crowd-sourcing project that specifically called on people to utilize low-build volume desktop 3D printers to produce functional ARs (Suchin, 2019). Moreover, outsourcing AR production to a 3DP company (e.g., D-Shape Company), which designs, prints, and ships ARs, offers an alternative to purchasing a 3DP on a smaller budget. Still, the more that reef managers and governments move towards restoration optimization technologies such as 3D imaging and 3DP, the lower the manufacturing costs will become, creating an avenue for specific restoration-based 3D technology.

Ultimately, there are potential drawbacks to the selected 3D printing modality and the chosen materials mentioned in Section 3.1 for 3DP ARs, such as bioplastics, various ceramics, and concrete. In the fabrication process it is important to consider the toxicity, binding agent of the selected material (capacity for erosion), the weight and structure of each material, and fragility. For example, polymers (synthetics) can be sensitive to UV light and saline water (Jacquin et al., 2019), whereas ceramics have been found to last millennia underwater (Carlson, 2003). Like most new technology, there are considerations and critical points to be resolved to increase efficiency. Although there are several massive on-land 3DP projects from large-scale 3D printers (Zastrow, 2020), until now there is no indication of implementing underwater structures at similar scales. Increasing scalability of 3D printed ARs will likely stem from the innovative potential of 3DP, either by mass-producing ARs from readily available 3D models, 3DP ARs directly underwater customized to the specific site (Mazhoud et al., 2019; Li et al., 2022), or 3DP ARs like building blocks from smaller or more accessible printers. This 3D interface still needs to sharpen the connection between the complexity parameters of a 3D image and the accuracy of the objected printed by the 3D printer. Understanding the required level of complexity to achieve the necessary functionality of a natural coral reef may prove more useful than trying to exactly replicate every detail. This concept encompasses different technological frontiers and applications that are not yet seamlessly intertwined, working towards automation to simplify the connection between each technology will streamline the process in the possible future. Using 3DP effectively for reef restoration activities, specifically for ARs, will require more knowledge of when to select this technology and how to apply it, depending on the objectives and long-term benefits.

## 5. Conclusions

With current projections estimating up to 90% of coral ecosystems will be severely degraded by 2050 (IM et al., 2019), there is a profound urgency to explore new interdisciplinary technologies that can be adapted and scaled to support coral ecosystems (Rogers et al., 2015). If we are to reach ecosystem or hectare-scale restoration for coral reefs and other marine habitats, we must invest in effective nature-based and sustainable solutions that can improve conditions, concomitantly to extensive climate action. The advantages of doing so, would lead to a positive socio-economic impact and long-term profits from environmental services, which in a decade or less could compensate the restoration costs (Saunders et al., 2020). In cases where standalone ARs may not be suitable, our methodology could be optimally adapted with other techniques, such as innovative materials like biocomposites that provide a sustainable and biodegradable substratum for marine organisms to grow (Contardi et al., 2021), or 3D CoraPrint, a process to create nature-inspired artificial coral skeletons from calcium carbonate photoinitiated ink (Albalawi et al., 2021), and 3D printed bionic corals capable of optical properties and housing algae (Wangpraseurt et al., 2020).

As the 3DP global market is expected to increase in value from roughly \$20 billion (USD) to \$56 billion by 2026, it will include printing technology, material, services, and software (BCC Research LLC, 2021), which could drive associated 3DP costs down. 3DP is already an inherently sustainable process with the potential to continue to reduce $CO_2$ emissions, material, and energy costs in both the short and long-term (Gebler et al., 2014). Incorporating ecosystem data (i.e., eDNA), 3D imaging, and 3DP for the fabrication of ARs is not just important for producing tailor-made biomimetic ARs to aid restoration, but it is also the future of sustainable production of large-scale restoration projects. Our custom data-driven 3D interface and an efficient evaluation toolkit could significantly upgrade current methods to produce more functional ARs to maximize restoration success.

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## CRediT authorship contribution statement

**N.L.:** conceptualization, methodology, investigation, data curation, writing – original draft, review & editing, formal analysis, visualization. **O.B.:** conceptualization, methodology, investigation, software, data curation, writing – original draft, review & editing, visualization. **M.Y.:** methodology, software, investigation, data curation, writing – original draft, review & editing. **Y.L:** validation, investigation, writing – review & editing, supervision. **T.T.:** conceptualization, methodology, software, investigation, writing – review & editing, supervision. **E.T.:** conceptualization, methodology, software, validation, writing – review & editing, supervision. **O.L.:** conceptualization, methodology, investigation, writing – original draft, review & editing, supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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