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Novel infrastructure for coral gardening and reefscaping

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Since 1950, coral abundance has declined worldwide by an estimated 60%, and further dramatic declines are predicted. Although global reductions in carbon emissions are essential to prevent further loss, coral reef restoration has become imperative to maintain the ecosystem services that coral reefs provide to humans at local scales. Yet, currently coral restoration and gardening efforts are too expensive to scale up due to the labor-intensive nature of the methods and low success rates. Here, we present a suite of technologies that improve coral reef restoration and rehabilitation's scalability, efficiency, and effectiveness. Our modular technologies are designed to streamline *in* and *ex situ* nursery workflows, reduce maintenance times, solve problems in transporting corals to outplanting sites, and enable rapid outplanting on natural and artificial substrates. These novel structures can act as coral seeding hubs, which placed strategically, can have the capacity to enhance coral reproduction and replenish degraded nearby reefs with larvae. They can be applied to coral restoration and reefscaping, complemented by unique eco-friendly, low-carbon-emission structures for the creation of architecturally and visually appealing habitats and underwater landscapes. Our technologies integrate novel monitoring approaches that support intelligent solutions to track genotypes, optimize and control stock management, apply assisted evolution approaches, and adaptive management through long-term monitoring.

KEYWORDS

restoration, maritechture, coral nursery, adaptive management, selective propagation, blue architecture, coral seeding hubs

1 Introduction

In the last 70 years live hard coral cover on coral reefs has declined by approximately 60 percent globally, which has been accompanied by a decline in the capacity of coral reefs to provide ecosystem services (Eddy et al., 2021). Even under moderate warming scenarios, a further loss of 75 to 95% of extant coral reefs is predicted by the end of this century (Frieler et al., 2013; van Hooidonk et al., 2016; IPCC, 2022). Increases in the frequency and severity of marine heat waves are expected to cause significant reductions in coral productivity, calcification, and survival in the next two decades (Klein et al., 2022). Therefore, substantial reductions in global carbon emissions and strict commitments to the Paris Agreement are essential to reduce a further loss (Kleypas et al., 2021). Provided the extent of realized and projected losses, coral reef restoration has become imperative to maintain the ecosystem services that coral reefs provide to humans at local scales (Hein et al., 2021). However, the biggest challenge remains implementing marine restoration efforts at scale, which are the most expensive and inefficient for coral reefs (Duarte et al., 2020). Currently, coral restoration projects are generally small, measuring only 500 m^2 per project in median (Boström-Einarsson et al., 2018). One of the most extensive coral restoration efforts to date was completed at Badi Island in Indonesia which involved the deployment of 7,000 m^2 of structures within an area of two hectares (Williams et al., 2019). However, Razak et al. (2022) describes a project in Indonesia creating up to 74.3 hectares distributed over five areas in Bali; notably with the effort of 10,000 people employed to plant nearly 96,000 units of artificial reef.

Unlike the culture of other marine species targeted for aquaculture, where productivity and yield have evolved over decades with dramatic technological innovations over the last 50 years, coral farming is still at the microscale due to a lack of industrial tools and difficult access to the marine environment (Gibbs, 2021). This contributes to the high costs associated with coral restoration, which is priced at a median of 404,147 \$US ha^{-1} (at the base year 2010) (Bayraktarov et al., 2019), with an uncertain success rate as few projects monitor survival long term beyond the time frame of the project (Boström-Einarsson et al., 2018). A recent review of patent and scientific literature data in the field of coral restoration highlighted a disconnect between technological innovation indicated by patent registrations, scientific findings and actual needs of coral restoration practitioners (Roch et al., 2023). The authors stress that research findings are often not translated into innovative and tangible management solutions. Further, market needs are not addressed by the majority of the technological innovations filed. Although the demand for coral restoration is rapidly growing, most projects are the size of a backyard, created using custom tools and solutions often specific to each project. Synthesizing the return-on-effort for the cost-effectiveness and viability of restoration efforts, Suggett et al. (2019) found no apparent change indicative of improved methodology over time. Large-scale projects demanding the implementation and driving the innovation needed for more industrial approaches and off-the-shelf solutions are still absent.

While restoration *via* transplantation on natural substrate is the most commonly practiced strategy, one-fifth of all projects create or add substratum such as artificial reefs (Boström-Einarsson et al., 2020). Artificial structures may be used for the augmentation of the reefscape to increase suitable substrates for coral transplantation, foster fish abundance *via* habitat creation, or tourist experiences (Boström-Einarsson et al., 2018). Working on ecosystems that are already suffering from carbon emission driven climate change and pollution, restoration efforts should aim to use environmentally friendly materials, avoid or minimize the use of plastic and target a low carbon footprint. Previously failed initiatives using old car tires for artificial reef construction, which had to be recovered at great expense (Sherman and Spieler, 2006), underscore the need to carefully select the materials used in reef restoration.

To reach ecologically meaningful scales in coral restoration, new solutions are needed to maximize efficiency in particular for marine operations. A significant bottleneck are the dive operations needed for outplanting and *in situ* coral bottleneck. For example, adhesion of a single coral during transplantation *via* epoxy takes up to ten minutes (Chamberland et al., 2017), adhesion with cement requires over five minutes per coral (Unsworth et al., 2021). One of the fastest methods for fragment attachment are the Coral clips, nails equipped with a metal clip to fixate the outplant, which require approximately one minute per coral (Suggett et al., 2020).

To reduce marine operations, coral aquaculture has been proposed as an ecological and economically viable solution for scalable reef restoration (CoralVita, 2019). To date coral aquaculture facilities are small-scale and frequently use conventional techniques such as tiles or plugs on plastic egg crates (Yanong, 2008; Craggs et al., 2019; Humanes et al., 2021). These types of facility require regular manual cleaning making maintenance of corals in nursery systems very labor-intensive. Although land-based systems are more easily accessible and, therefore, easier to maintain than *in situ* coral nurseries (O'Neil, 2015), the workforce has been identified as the main challenge across different coral gardening methods (Hein et al., 2021). While integrating volunteers or citizen scientists can in part compensate for high workforce requirements in smaller projects (Hesley et al., 2017), commercial endeavors at scale would not be able to rely on this approach. Hence, more innovative and advanced technologies are required to streamline workflows and reduce labor-intensity to reach meaningful industrial scales of production.

Here we describe the first-ever modular suite of coral restoration technologies, invented specifically to simplify and increase the efficiency of critical workflows, from coral husbandary, substrate creation and outplanting. Each coral restoration technology described is inter-compatible, and can be used alone or in combination, targeting flexibility, scalability and cost effectiveness. We provide a solution for rapid reefscaping using quickly deployable artificial structures. Rethinking coral restoration efforts from an industrial scale perspective, the presented technologies are the first engineered solution with the potential to enable large scale farming operations.

2 Materials and equipment

The designs described here are registered under the trademark Maritechture™ and patented to ensure they are consistently engineered and to facilitate economies of scale at the point of production, thereby reducing the cost of each element.

2.1 Screwable coral tiles

Maritechture™ screwable coral tiles have an internal thread that allows quick and tool free attachment to several other products outlined below in the following. Tiles are made from cement and shapes can be modified to cater for different propagation pathways, e.g. fragmentation, microfragmentation (Forsman et al., 2015) and recruitment (Figures 1E, B, C). We chose a hexagon shape for propagation of larger fragments, which allow easy screwing (Figure 1D). For propagation *via* micro-fragmentation, where a larger flatter surface is preferable, we developed a flatter hexagonal shape to promote the overgrowth of the surface (Figure 1B). For sexual propagation *via* larvae settlement, we developed a shape with multiple cavities to promote settlement. An RFID (radio frequency identification) chip can be embedded within the cement tiles, enabling long-term labelling of individual tiles (Figure 1F) and allowing for the identification and tracking of origin, performance and survival throughout restoration or enhancement efforts.

2.2 Coral crates

Maritechture™ coral crates (Figure 2) are racks of durable, UV-resistant ABS plastic that allow coral tiles to be attached *via* threaded pins erected vertically from linear extrusions (Figures 1A, B). The design allows multiple tiles to be attached per frame, arranged in a uniform and equally spaced pattern. The crates are stackable and click into each other, creating a 10 cm gap between each level. Each row is pre-labelled, and the crates can be equipped with RFID tags or QR codes for organization of tiles. In their current design, each unit measures 50 x 50 x 15.5 cm and can hold up to 56 fragments. The crates have holes in their legs for horizontal connection of multiple crates, allowing, for example, the quick set-up of *in situ* nurseries.

2.3 Coral outplanting/nursery devices

The modular tile system allows for easy attachment and removal of propagated corals by screwing and provides great flexibility for different types of coral gardening and outplanting. Maritechture™ Reef Nails (patent pending) are threaded nuts that, when combined with a standard stainless-steel concrete/masonry nail, can be easily embedded in solid reef substrates and expose a thread that matches

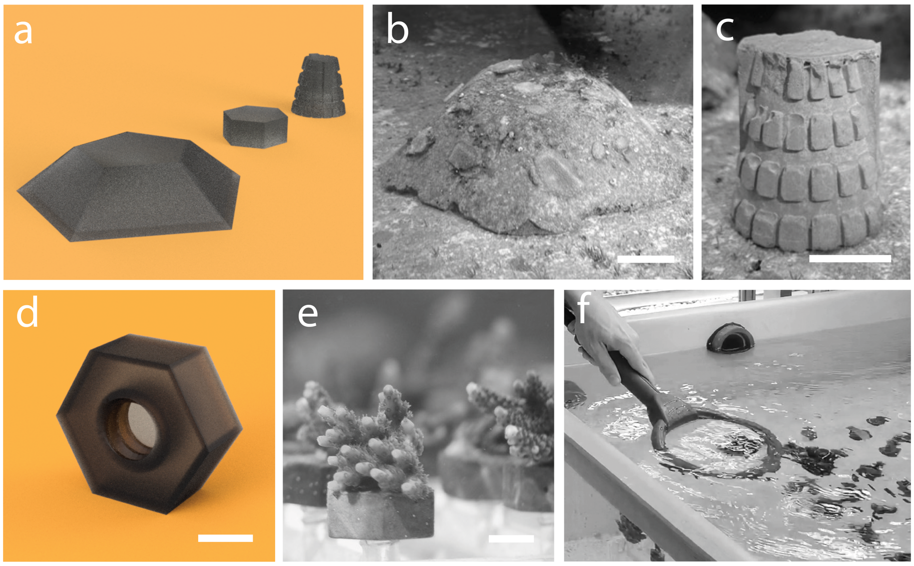

FIGURE 1
Maritechture™ Screwable coral tiles (patent pending, U.S. Patent Application No. 17/767,251Filed April 7, 2022). **(A)** Different shapes to cater to different propagation pathways. **(B)** Microframentation tile. **(C)** Recruitment tile. **(D)** Fragment tile. **(E)** Coral tiles attached to the coral crate. **(F)** Trackable tiles are RFID microchipped and can be identified using a conventional chip reader, which can be operated underwater. White bar indicates 1 cm in width.

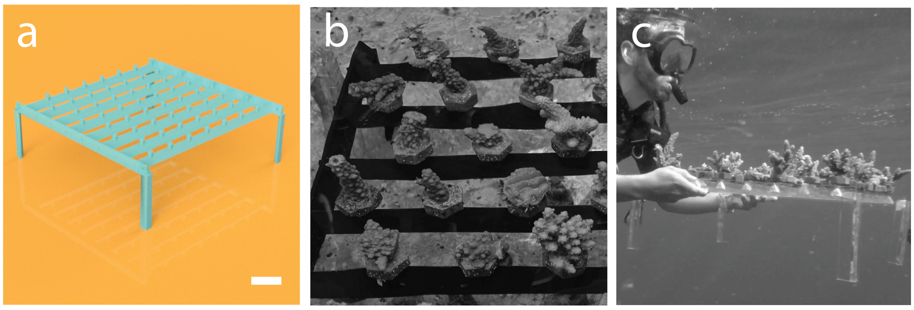

FIGURE 2
Maritechture™ Coral crate (patent pending, 63/187,218 and 29/783,128, "Coral farm crate and methods of use thereof" May 11, 2021). **(A)** Stackable coral crate. White bar indicates 10 cm in width. **(B)** Coral tiles on coral frame. **(C)** Easy and safe transport of corals.

the coral tiles (Figures 3A, B). The nut fits tightly around the nail to avoid rotation but can be secured with additional adhesives if needed. Maritechture™ Reef Wall Plugs (patent pending) have the same function but are attached with a steel screw similar to a standard wall dowel (Figures 3C, D). They allow for quick and solid attachment of coral tiles to surfaces with predrilled holes, such as artificial structures.

To equip existing coral gardening infrastructures with our technology, we have developed several solutions (patents pending): Maritechture™ Clips for PVC pipe nurseries [e.g., coral tree nursery© (Nedimyer et al., 2011)(Figure 3E)], Maritechture™ adapters for steel rod/metal frame nurseries (e.g. Williams et al., 2019) that can be fastened with cable ties (Figure 3F), Maritechture™ adapters for aluminum frame/grid nurseries (e.g. Suggett et al., 2019) that can be fastened with cable ties (Figure 3G), and adapters for rope nurseries (e.g. Levy et al., 2010) that can be twisted into the rope and expose two sides for tile attachment (Figure 3H).

2.4 Coral pods

To provide a stable artificial substrate for coral outplants where this is lacking, we developed Maritechture™ Coral Pods, which are limestone structures consisting of two plates that can be assembled at 90-degree angles to form a quattro pod (four-legged stand) like structure (Figure 4). Drilled holes along the top edge allow coral fragments to be attached with cable ties or Maritechture™ Reef Wall Plugs (Figure 3C). Additional holes in the center of the segments provide an ideal place for massive corals to be attached using our tile system. The shape and size (with individual panels approximately 145 cm long, 47 cm high, and 3 cm thick) aim to minimize waste during production and allow ergonomic handling, so the weight of each limestone segment is limited to approximately 20 kg (Figure 4C). The design provides stability in low to medium-energy environments. However, these dimensions and design (including number of stacked plates) can be adjusted depending on the available limestone slab sizes and the intended use.

3 Method description

Our modular infrastructure for coral restoration and reefscape enhancement has been designed to streamline various elements of the coral gardening process from husbandry to outplanting (Figure 5) and facilitate data logging and monitoring.

3.1 Donor

With our technologies, corals may originate from sustainable harvesting (Rinkevich, 1995; Barton et al., 2017), fragments of hope (Garrison and Ward, 2012), coral relocation sites (Kenny et al., 2012), or nursery/growth operations (Rinkevich and Shafir, 2000; Barton et al., 2017). Propagation can be asexual by fragmentation (Rinkevich, 1995) or sexual by cultured (Petersen and Tollrian, 2001) or wild-caught larvae (Doropoulos et al., 2019) (Figure 5). Regardless of origin, it is critical to collect as much metadata as possible on the corals to inform husbandry conditions and to direct downstream applications (Baums et al., 2011). This includes the GPS coordinates of the sample location in the case of wild-sourced corals or the origin of the donor/parental lineages in the case of husbandry. The sampling date, size, species, depth, temperature, light conditions, etc., should also be provided. These data should be recorded and stored in a central database (Figure 5) to inform performance assessments and optimize future deployments.

3.2 Screwable coral tiles

Transplanting fragments or seeding larvae using trackable Maritechture™ Coral Tiles allows metadata to be associated with individuals *via* RFID tags. This information can guide culturing conditions during husbandry, for example, regarding light levels. Embedding the RFID tag into the transplant or seeding substrate allows for permanent long-term identification and efficient stock

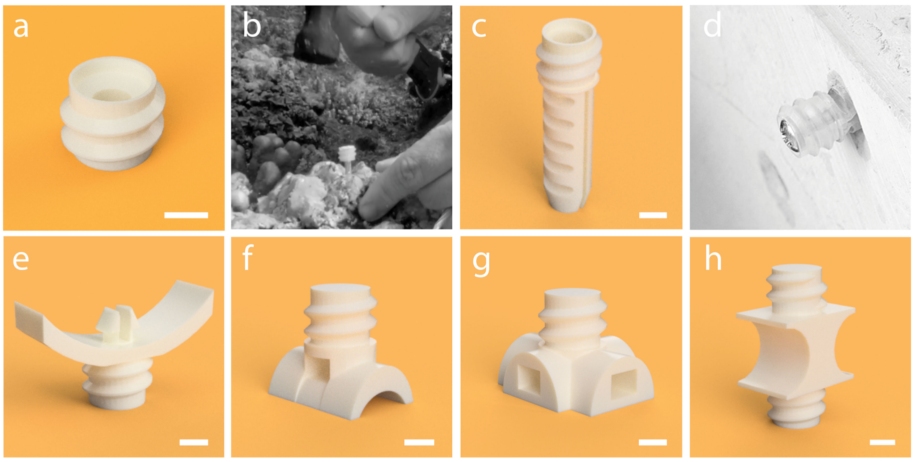

FIGURE 3
Devices for different outplanting/nursery types. **(A, B)** Maritechture™ Reef nails for outplanting on natural substrate (patent pending) **(C, D)**7 Reef wall plug for outplanting on coral pods, harbor walls, etc. (patent pending) **(E-H)**. Tools to equip existing nurseries. **(E)** Clip for PCV pipe nurseries. **(F)** Adapter for steel/bar nurseries. **(G)** Adapter for aluminum frame/grid nurseries. **(H)** Adapter for rope nurseries. White bar indicates 5 mm in width.

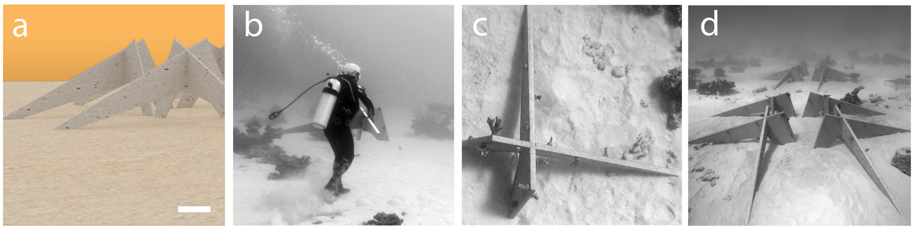

FIGURE 4
Maritechture^{TM} Coral pods (patent pending, U.S. Patent Application No. 62/954,435| Filed December 28, 2019). **(A)** Illustration of coral pod design. White bar indicates 20 cm in width. **(B)** Diver placing coral pod underwater. **(C)** Coral pod with coral fragments *in situ*. **(D)** Arrangement of coral pods.

management (Schmidt-Roach et al., 2020). It will enable monitoring and tracking of individual colony performance, stress susceptibility, health and survival during culture and beyond, all of which can be related back to colony origin and history. If individuals die, the tiles can be cleaned and reused.

Tagged tiles are equipped with passive integrated transponders (PIT) based on radio frequency identification (RFID) with low-frequency operation (134.2 kHz) and 64-bit identification. The tags can be read with any PIT reader compatible with the ISO 11785 standard. When used in conjunction with inventory management software, this solution allows corals to be tracked as they are propagated or moved between tanks *ex situ* or sites/structures *in situ* to automatically update records. This enables real-time automated stock management to coordinate aquaculture and allocate harvestable colonies to outplanting efforts. We are currently prototyping software customized for this purpose.

For fragmentation, we use various standard cutting techniques such as bone cutters or a Gryphon Diamond Band Saw (AquaSaw). Adhesion of coral fragments to tiles or plugs is performed using various methods, including epoxy (e.g. Hein et al., 2020) or ultraviolet (UV)-curable oligomer-based adhesives (Takeuchi et al., 2019), or commercially available gel-based cyanoacrylate adhesives. It is important that the fragment's tissue has grown over the tiles prior to outplanting, as the adhesion of the adhesive often wears off over time. It has been shown that coral fragments from branching species attached upside down grew significantly wider and faster over the tiles than corals attached right side up (Tagliafico et al., 2018), and we recommend this technique to promote rapid tile overgrowth.

The shape of the tile can be adjusted to the propagation pathway (Figure 1). For fast-growing, branching species, we recommend small hexagonal tiles (Figure 1E). For slow-growing, massive species, we recommend larger tiles that allow the use of standard microfragmentation protocols (Figure 1B) (Forsman et al., 2015). For recruitment, we recommend structured tiles with small cavities, which have been shown to promote larval settlement (Nozawa et al., 2011; Randall et al., 2021).

3.3 Coral crates

Attachment of the tiles to the Maritechture^{TM} Coral Crates supports the strategic organization of corals. The crates allow coral genotypes to be organized in rows divided into seven tiles per bar (labelled A-H on the crate) (Figure 2A). Secure attachment by the screw system avoids friction and damage to the colonies (Video 1). The coral crate units facilitate easy handling in air and underwater and simplifies cleaning during aquaculture because of their smaller surface area compared to commonly used egg crate grids. The crates can also be tagged with RFID technology, allowing for automated inventory management. For transportation, the units can be safely stacked and transported directly to the outplanting site underwater. In addition, the horizontal connection of multiple crates and attachment to the seafloor enables the rapid establishment of *in situ* nurseries, e.g. for temporary storage.

3.4 Coral outplanting/nursing devices

We have developed several solutions for outplanting (Figure 3). The advantage of our modular, screwable tile system is that coral crops can be quickly interchanged between crates and different structures or outplanted directly onto a natural or artificial substrate. We have developed adapters for the most common types of coral nursery structures including PVC pipes, metal rods, metal grids and ropes (Boström-Einarsson et al., 2020). This allows existing structures to be quickly modified and outfitted to accommodate our technologies.

Our Maritechture^{TM} Reef Nails attach quickly (within seconds) to suitable reef substrate and create a solid bond that promotes attachment of the fragments to the reef substrate. A single dive buddy team can outplant over 50 fragments from a coral crate onto reef substrate in 30 minutes. For artificial structures that can be drilled with holes prior to deployment, we developed Maritechture^{TM} Reef Wall Plugs. Similar in function to a conventional dowel, these allow for a solid connection of our tiles to artificial substrates such as Maritechture^{TM} Reef Pods, jetty walls, floating villas or bridge piers.

3.5 Coral pods

We developed Maritechture^{TM} Coral Pods as an environmentally friendly underwater landscaping tool to enhance reef landscapes and provide new substrate for coral outplanting and nursing where this is lacking. With our methods, we envision their use for the creation of artistically planned and curated underwater landscapes, whereby the structures can be arranged in geometric patterns for visual and orientation purposes. The units can be stacked flat on top of one another to minimize space requirements and ease transport and logistics costs. On-site, the coral pods can be quickly assembled either on board a vessel or underwater. The corals can be attached with Maritechture^{TM} Reef Wall Plugs or cable ties.

In their current design, each assembled structure can accommodate up to 16 coral fragments. Given an area of 1.5 m^2 for coral growth per structure, we recommend a density of one structure per 3 m^2. With 14-16 corals per structure, this results in an outplanting density of approximately five corals per square meter, which may increase further with spontaneous natural recruitment, given that the material is highly suitable for coral settlement. By mounting the structures onboard a vessel, corals can be quickly attached before the pods are placed in the water, reducing dive time. In this way, a team of six can deploy up to 30 structures per dive, with four team members assembling the structures, stocking them with coral and lowering them with a crane, while two divers receive and position the structures on the seabed at the deployment depth. On rotation, a six-person construction team can place 90 structures in four hours, with each team member performing only a single dive. This allows for up to 250 square meters of reef landscape to be created in half a day.

4 Discussion

Coral restoration efforts are still limited by a lack of industrial-scale commercially available tools to facilitate cost-effective operations at

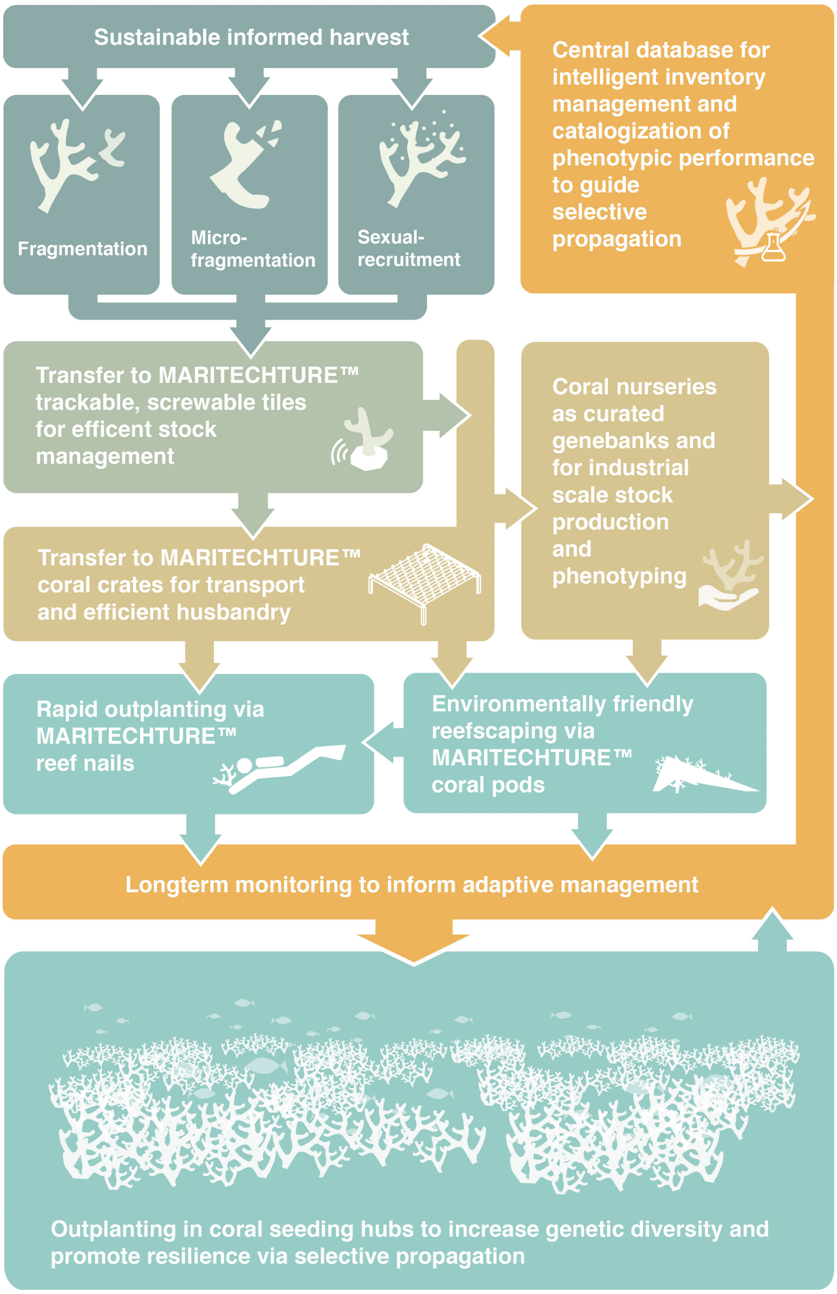

FIGURE 5
Schematic workflow illustration of an adaptive management approach.

scale. Although there is no one-size-fits-all solution for coral restoration, our modular technologies provide flexibility to create new or to adapt to and upgrade and improve existing infrastructure and techniques. Our technologies address aquaculture, coral gardening, substrate creation, outplanting and monitoring workflows, providing the first holistic, modular toolset for coral restoration and reef expansion, and enabling an adaptive management approach. Previous technologies only targeted individual applications or workflows and often have limited scalability.

For substrate creation, Reef Balls™ (Sherman et al., 2002) or similar derivations, are likely the most widely distributed commercial solution for reef habitat creation and coastal protection. Attachment of corals to these structures is usually achieved using epoxy, which is time intensive and carries risks of toxicity. Although not commercially distributed as off-the-shelf-product, Mars Reef Stars offer a standardized design for metal frames that can be interconnected to restore damaged reefs (Williams et al., 2019). These structures are usually custom made at each location from steel rods coated with epoxy and sand, and corals are then attached *via* cable ties. The Maritechture™ Coral Pods presented here are similar in functionality to Mars Reef Stars, however, due to their innate weight they do not require interconnection. Further, unlike steel, limestone is an environmentally friendly material known to enhance coral recruitment (Schmidt-Roach et al., 2008). Hence the structures are self-seeding and with their relatively large surface (approximately 2.5 m^2) quickly develop a natural reef-like patina on their surface. Per square meter, our Maritechture™ Coral Pods have an estimated carbon footprint of about 80 times less than Mars Reef Stars and over 800 times less than a standard Reef Ball (Table 1). Constructed from natural limestone, our structures are reef-like and do not alter the water chemistry. Further, they have no plastic coatings that may break down to micro-plastic over time.

4.1 Towards coral restoration at scale

To increase scalability and overcome time intensive adhesion during outplanting, Suggett et al. (2020) developed Coral Clips®, a fast solution to outplant fragments or tiles *via* a metal clip attached to a nail hammered into the reef. Similar in function to the Maritechture™ Coral Nails presented here, these work well on hard substrate and allow strategic placement of fragments during outplanting. While Coral Clips® are ideal to reattach so-called fragments of hope (lose fragments broken of larger colonies for example during storms), growing and attaching coral directly to their outplanting substrate *via* our Maritechture™ Coral Tiles minimizes the stress that may occur during detachment of corals after an intermediate gardening phase. Further, our tiles have the advantage of enabling long-term monitoring.

To avoid the need for dive operations at all during outplanting, Chamberland et al. (2017) proposed ceramic tetrapod structures seeded with coral recruits to be deployed from vessels into reefs. Although this permits the economic deployment of a large number of structures, tests need to be conducted to understand survival rates compared to recruitment tiles strategically placed using the Coral Clips® or Maritechture™ Reef Nail technology. Doropoulos et al. (2019) went a step further to propose industrial-scale harvesting of larvae *via* large vessels for relocation, whereby the mass of harvesting of coral larval slicks can be deported to foreign reefs to overcome the low survivorship of settlers. However, large scale pilot studies are still to be conducted.

Our Maritechture™ technologies provide the basis to enable the automation of coral reef restoration workflows in the future. Coral aquaculture can achieve higher production rates by optimizing conditions for increased growth, e.g. by adjusting light or temperature, or by co-culturing of beneficial biota and reducing algae growth (Craggs et al., 2019). However, optimal husbandry conditions can be species-specific (Merck et al., 2022). The organized placement of coral colonies on the coral crates allows quick and strategic performance assessments to ensure individuals are fostered under ideal conditions. Having coral fragments in fixed positions in the tanks may eventually facilitate AI-driven automated phenotyping, for example, *via* repeated structure from motion photometry using robotic solutions. Similar techniques are already in place in terrestrial systems to increase production rates and promote selective breeding (Humplík et al., 2015; Chawade et al., 2019). High-throughput phenotyping could enable big data analytics, which could dramatically increase production rates and the effectiveness of coral nursery efforts. Considering the current rise of applied use of robotic systems in fish farming (Wang et al., 2021) or even more distant sectors as part of the industry (Javaid et al., 2021), automatization of workflows is likely to play a significant role in reducing associated labor costs and achieving scale.

TABLE 1 Carbon footprint of different coral support structures. Greenhouse gases produced associated with construction is estimated based on Hammond and Jones (2008).

Type	Material	Approx. weight kg	$KgCO_2$ emission/kg	$kgCO_2$ emission per unit	Area in m^2	$kgCO_2/m^2$ emission	Reference
Maritechture™ *Coral pod*	Limestone	40	0.017	0.68	1.5	0.5	This study
Mars Reef Star	Steel rod (excluding epoxy)	8	1.71	13.68	0.34	40.6	(Williams et al., 2019)
Reef Ball	Cement (Portland)	1364	0.83	1132.12	2.63	430.5	www.reefball.org/technicalspecs

4.2 A tool for stakeholder engagement, outreach, and education

The ability to create detailed records and to trace performances over time using our trackable Maritechture™ Coral Tile technology enables unique information tools for stakeholder engagement. Creating cloud-based inventories and data records can not only guide coral restoration practitioners during their daily efforts, but it can also be used to inform stakeholders (e.g. governments or private entities investing into these efforts) about the success. Measuring and publishing performance can promote transparency and assist moderate expectations of the success of restoration efforts. Trust has been shown to significantly strengthen willingness to pay for restoration (Metcalf et al., 2015; Bakaki and Bernauer, 2016). In addition to building trust, communicating success as well as challenges on websites or social media may motivate public engagement and foster awareness. Projects could use this mechanism to transport positive messages of hope, which are important to gain public acceptance for government-funded restoration projects (Le et al., 2022).

4.3 Integrating selective propagation

For selective propagation efforts, it is vital to create detailed records to trace performances over time to permit adaptive management (Schmidt-Roach et al., 2020) and identify possible tradeoffs associated with the selected traits. Different pathways for thermal heat selection have been identified (Baums et al., 2019; Parkinson et al., 2019; Schmidt-Roach et al., 2020; Voolstra et al., 2020; Suggett et al., 2022). However, when comparing individuals from different environments, it should be considered that these may be phenotypically acclimated to different conditions, which may alter their performance in acute thermal stress assessments. Common-garden nurseries *ex* or *in situ* offer the advantage that individuals can be acclimated to similar conditions prior to testing, which may reduce acclimation biases during performance assessments. Although different strategies for selective breeding of corals for assisted evolution have been suggested (van Oppen et al., 2015; van Oppen et al., 2017) and partially tested (Humanes et al., 2021), the long-term effect and success of these strategies still remain uncertain. Our trackable tile system *via* RFID technology supports long-term monitoring efforts and permits informed adjustment of selective propagation strategies. In addition to RFID identification, the embedded stainless-steel nail in our reef nail solution can be detected using a metal detector similar to CoralClips® (Suggett et al., 2020).

Strategic outplanting can further increase genetic diversity and stress resilience, as restored corals have been observed to be reproductively active (Diraviya Raj et al., 2015). Coral pods and reef nails can be used to create coral seeding hubs (CSH), where different genotypes of conspecifics are planted in clusters strategically placed in the reef to promote reproduction and increase genetic diversity in the offspring (Schmidt-Roach et al., 2020). A portion of these transplants can be sourced from selected, higher stress resistant colonies to increase the frequency of favorable alleles in the population while maximizing genetic diversity (Schmidt-Roach et al., 2020). However, not all genotypes should be selected for increased single stress performance, and genetic diversity should be maximized to account for unforeseen stressors such as disease (Moriarty et al., 2020).

4.4 Towards a blue architecture and landscaping approach in coral restoration

In contrast to present coastal developments that rarely extend beyond the shoreline, we advocate for a “blue architecture” and landscaping approach that extends landscaping of coastal developments into the sea. Community-conscious coastal developments that integrate the marine environment may secure natural capital (Cziesielski et al., 2021). Schmidt-Roach et al. (2020) stressed the mutual benefit of integrating coral restoration efforts in coastal developments to rehabilitate natural habitats and foster and secure blue natural capital as part of development assets. In addition to conventional restoration operations, the elements, tools and processes presented here allow easy and quick beautifications of jetty walls and other coastal structures with corals, turning these into meaningful resources to grow corals for restoration and to create or restore fully functional habitats.

A blue architecture and landscaping approach to coral restoration requires the contribution of a multidisciplinary team including marine ecologists, engineers, architects and artists, forming a community of practice that extends well beyond the competencies applied in conventional coral restoration projects. Applying a landscaping approach, our techniques allow the creation of scientifically and artistically curated underwater habitats resembling land-based botanical gardens. Architecture that extends into the sea connects coastal residents with their natural marine resources, engages citizens with restoration, raises awareness, promotes responsible stewardship, and boosts local economies. This may especially be of interest for ecotourism projects providing a dual benefit of attracting visitors and increasing resilience hence securing investments (Schmidt-Roach et al., 2020). Visionary plans for floating cities to address sea-level rise and overpopulation have become more concrete (Bolonkin, 2011; Wang, 2019) and offer unique opportunities for integrating marine landscape designs into marine urban projects. Massive tropical floating cities such as Oxagon envisioned by NEOM (https://www.neom.com/en-us/regions/oxagon) or Oceanix by BIG (https://big.dk/#projects-sfc) could be easily adjusted to harbor coral farming using the technologies presented here.

In conclusion, our platform aims to provide simple, eco-friendly and flexible infrastructure that caters towards a variety of different coral restoration and reefscaping efforts with a view of rendering coral restoration more cost-effective, scalable and sustainable. This is achieved by reducing workflow times as outlined above and ease of handling. Integrating novel monitoring tools, our approach delivers an intelligent solution to optimize and control stock management and enables adaptive management. The modularity of the tools aims to allow greater flexibility as different components can be added in the future to increase efficiency and effectiveness. We aim to make the above-described solutions available as the first modular off-the-shelf coral restoration technology, targeting production at scale to drive down costs, and to make them universally available.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Ethics statement

Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

Author contributions

SS-R invented, designed, and prototyped the technologies with contributions of all authors. SS-R prepared the manuscript, which was revised and improved by all authors. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The patents for the technologies were filed by King Abdullah University for Science and Technology KAUST with SS-R, MA, CD, and CH as inventors. SS-R, CD, MA, AA-S, and RK are shareholders of Ocean Revive Company (ocean-revive.com), which targets to commercially distribute the technologies and make them available to coral restoration scientists and practitioners globally. Author JC is the founder of company Studio Julian Charrière.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1110830/full#supplementary-material

SUPPLEMENTARY VIDEO 1
Deployment and use of the Maritechture™ technologies.

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