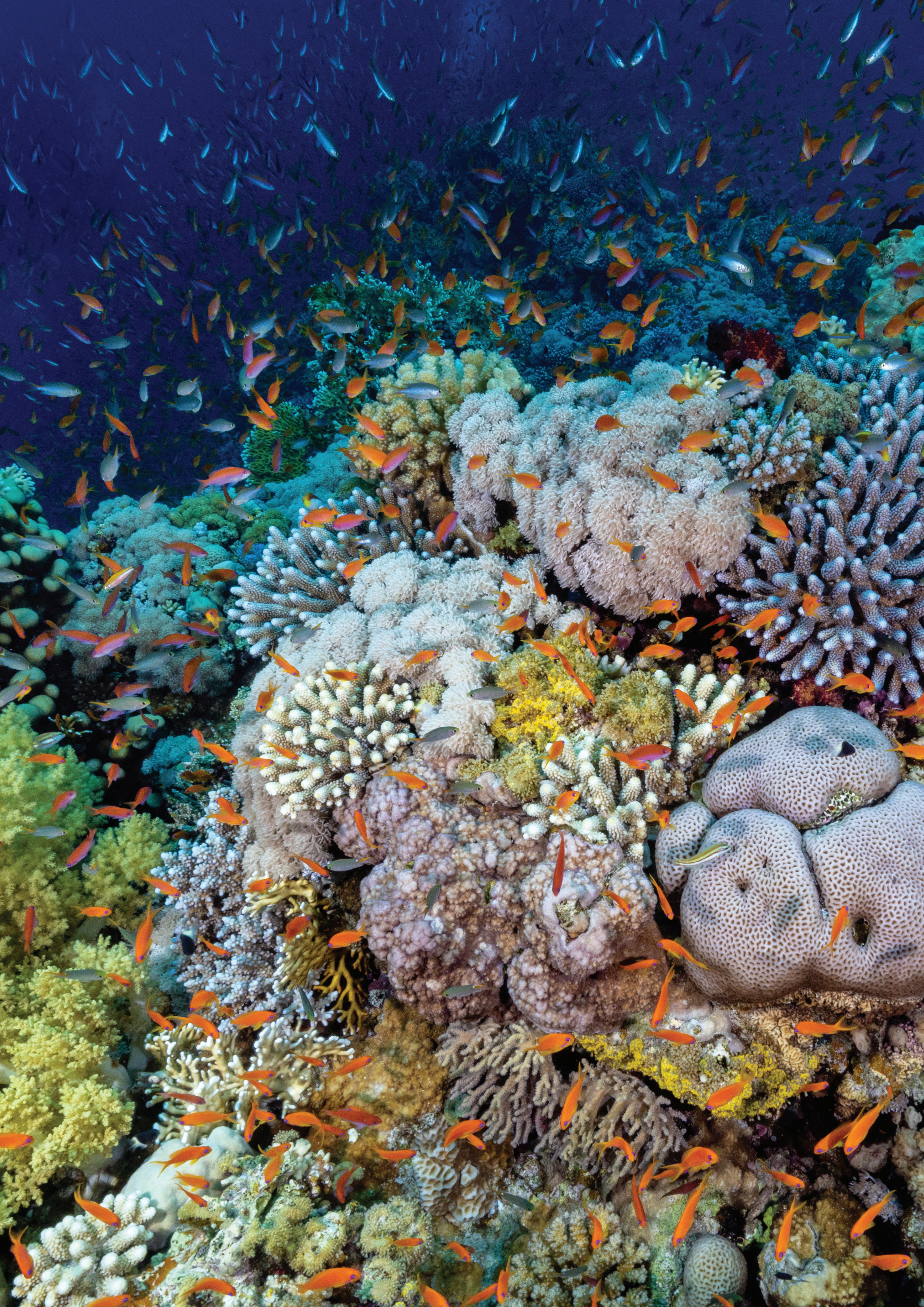
EXPLORING THE FRONTIER OF CORAL AQUACULTURE

CORDAP R&D TECHNOLOGY ROADMAP

cordap
Coral Research & Development Accelerator Platform

كاوست مبادرة إحياء الشعاب المرجانية
KAUST Coral Restoration Initiative

جامعة الملك عبدالله للعلوم والتقنية
King Abdullah University of Science and Technology



Credit: KAUST Coral Restoration Initiative

Table of contents

Organizing committee:

Prof. Carlos Duarte
Dr. Sebastian Schmidt-Roach
Mr. Tom Moore
Mr. Gator Halpern
Ms. Cassandra Roch
Dr. Maram Abadi

Report preparation:

Dr. Sebastian Schmidt-Roach
Ms. Cassandra Roch
Dr. Lutfi Afiq-Rosli

With contributions from:

Dr. Adriana Humanes
Mr. Andrea Severati
Dr. Carmela Isabel Nuñez Lendo
Prof. David Suggett
Dr. Elizabeth Goergen
Dr. Jason Spadaro
Dr. Carol Buitrago-Lopez
Dr. Anderson Mayfield

Participants:

Dr. Adriana Humanes, Newcastle University, United Kingdom
Mr. Andrea Severati, Australian Institute of Marine Science (AIMS), Australia
Dr. Andreas Hutahaean, Ministry for Maritime Affairs, Indonesia
Dr. Jamie Craggs, Horniman Museum and Gardens, United Kingdom
Dr. Carmela Isabel Nunez Lendo, University of Technology Sydney, Australia
Dr. Jason Spadaro, Mote Marine Laboratory & Aquarium, United States
Mr. Manyu Belani, Reefgen, United States
Dr. Matt Campell, Natrx, United States
Mr. Scott MacDonald, Seafoundry, United States
Dr. Carol Buitrago-Lopez, Red Sea Global, Saudi Arabia
Dr. Zenon Batang, King Abdullah University of Science and Technology (KAUST), Saudi Arabia
Prof. David Suggett, KAUST, Saudi Arabia
Prof. Manuel Aranda, KAUST, Saudi Arabia
HH Shaikha Al Saud, Red Sea Global, Saudi Arabia
Dr. Shannon Klein, KAUST, Saudi Arabia
Dr. Yousef Al-Hafedh, National Center of Wildlife Research, Saudi Arabia
Mr. Sam Marshall, Partanna, Bahamas
Mr. Rick Fox, Partanna, Bahamas
Mr. Adrian Tolliday, KAUST, Saudi Arabia
Mr. David Mead, AIMS, Australia
Mr. Amir Matouk, KAUST, Saudi Arabia
Dr. Elizabeth Goergen, KAUST, Saudi Arabia
Dr. Zac Forsman, KAUST, Saudi Arabia
Mr. Gator Halpern, KAUST, Saudi Arabia
Dr. Sebastian Schmidt-Roach, KAUST, Saudi Arabia
Mr. Tom Moore, KAUST, Saudi Arabia
Prof. Carlos Duarte, KAUST, Saudi Arabia

Workshop protocolists:

Dr. Lutfi Afiq-Rosli, KAUST, Saudi Arabia
Dr. Holger Anlauf, KAUST, Saudi Arabia
Mr. Alejandro Prieto, KAUST, Saudi Arabia
Ms. Eleonora Re, KAUST, Saudi Arabia
Ms. Nayra Pluma, KAUST, Saudi Arabia

Organization support:

Ms. Madhvi Naganand, CORDAP, Saudi Arabia
Ms. Guiomar Duarte, CORDAP, Saudi Arabia
Ms. Hiroko Davis, CORDAP, Saudi Arabia
Ms. Areej Alghamdi, KAUST, Saudi Arabia

Cite as:

Schmidt-Roach S, Roch C, Afiq-Rosli L, Humanes A, Severati A, Nuñez Lendo CI, *et al.* (2024)
CORDAP R&D Technology Roadmap for Exploring the Frontier of Coral Aquaculture.

Executive summary

Credit: KAUST Coral Restoration Initiative

1.1 Background

Climate change and other anthropogenic impacts have led to unprecedented levels of coral reef decline on a global scale. Further deterioration is predicted by the end of this century under current carbon emission reduction pathways.

Along with enhanced efforts to rapidly lower climate gas emissions, we face an imperative to restore, rehabilitate, and maintain marine habitats to secure the ecosystem services they provide.

While terrestrial restoration projects have benefited from the agricultural revolution, which has provided industrial-scale tools for effective habitat restoration and rehabilitation, slower technological transformation in the marine sector, in addition to limited accessibility, has resulted in a lack of cost-effective and scalable solutions for coral reef restoration.

To address the fundamental challenges in advancing the upscaling and effectiveness of coral reef restoration, an in-person workshop was held from the 29th to 31st of January 2023 at the King Abdullah University of Science and Technology (KAUST), Saudi Arabia, bringing together international academic, industry-based, and technology experts from various fields, including scientists in coral reef biology and ecology alongside experts in marine (including coral) restoration, engineering, and aquaculture.

The workshop aimed to promote interdisciplinary dialogue among participants with the goal of identifying priority areas where investments in research and development (R&D) would enable transformative, cost-effective practices of coral aquaculture and outplanting at scale.

Workshop participants were specifically tasked with exploring the technological advancements required for upscaling coral restoration efforts to achieve ecologically significant impacts, with an emphasis on:

a. Industrial land- and ocean-based coral nurseries,

b. At-scale outplanting and monitoring, and,

c. Assisted evolution-based strategies aimed at improving propagated coral resilience.

The experts' evaluations were then analyzed and discussed according to four critical components:

1. Lead-time
2. Quality
3. Cost
4. Flexibility

In doing so, the approach aimed to describe the potential for each solution to deliver efficient and effective coral reef restoration at scale.

Collectively these steps were used to identify critical priority areas that could benefit from strategic investment to most rapidly advance reef restoration solutions.

1.2 Program priority areas

Workshop participants identified that substantial investment from CORDAP and/or other funding agencies is needed to support R&D for the following topics to effectively upscale coral reef restoration.

Infrastructure for coral production

Coral reef restoration technologies are currently non-commercial and custom-made, with few standardized, "off-the-shelf" (i.e., modular), operational designs available. Effectively upscaling coral reef restoration efforts will require infrastructure that features low-cost unit economics associated with high-throughput coral production. Priority areas to address these include:

a. Standardization and modularization of infrastructure, from coral substrate materials to nursery and outplanting components (e.g., modular life support systems [LSS], standardized *in situ* nursery systems, and final outplant products).

b. Reduction of maintenance needs for infrastructure (e.g., incorporating mechanical, biological, and/or chemical antifouling solutions and technologies).

c. Solutions for the enhancement of coral growth, performance, and survival (e.g., improved light, temperature, and flow regimes; materials science approaches for coral growth/development substrates; and tank space optimization).

Management and workflows

A major bottleneck to upscaling coral reef restoration efforts is the massive time and labor investment required throughout the production pipeline, mostly related to stock and inventory management. To overcome these bottlenecks, efficient coral production and management workflows were highlighted as priorities, with an emphasis on:

a. Semi or, fully-automated inventory systems for stock management.

b. Efficiency of asexual and sexual propagation.

c. Standardized software/hardware to optimize data collection and production.

d. Development of holistic modeling tools that incorporate key coral production success factors (e.g., costs, survival, growth, health, environmental conditions), enabling production/outplant simulations and improving decisions, designs, and R&D investments.

Integrating resilience into coral reef restoration efforts

For coral reef restoration efforts to succeed in the face of climate change, resilience-focused strategies, in particular those that can integrate assisted evolution-based approaches at scale and at high-throughput, must be developed. The following areas were identified as key priorities for implementing assisted evolution approaches at scale:

a Phenotyping/genotyping assays to assess stress tolerance.

b. Protocols for selective breeding.

c. Coral symbiont/microbiome manipulation and enhancement methods (e.g., application of probiotics or infection with heat-tolerant dinoflagellates).

d. Environmental hardening (e.g., thermal stress-hardening).

e. Co-culture and polyculture.

Efficient outplanting

Arguably, the step that limits cost-effective coral reef restoration is outplanting. There is a need to develop new tools and operations that can advance outplanting, namely:

a. Semi- or fully-automated outplanting (i.e., reducing or eliminating the diver-coral interaction time).

b. Strategies/techniques to increase long-term survival of outplants (e.g., environmental priming of receiving sites).

c. Optimizing design of coral-bearing devices that can be deployed without divers and effectively attach to most types of natural or artificial structures.

Monitoring

Capacity to demonstrate successful restoration is critical and involves effective monitoring over space and time of all processes (e.g., from nursery propagation to monitoring of restoration and reference sites). Major needs remaining to develop more effective monitoring strategies include:

a. Cost-effective and long-term collection of both environmental and ecological data (e.g., sensors, sensor arrays, and automated image/data collection).

b. Cost-effective and accessible data storage solutions, efficient global data transfer, and advanced (automated) data processing and analysis.

c. Database design and curation and data integration with computer vision, image classification algorithms, and other fields of artificial intelligence (AI).

1.3 Rational for the identified priority areas

1. A fundamental need is for efficient and low-maintenance coral aquaculture. Current approaches mostly lack standardization, which inflates the cost and constrains their scalability.
2. Current median coral production costs (~$10USD as of 2010; Bayraktarov *et al.* 2019) limit the scale of landscape or global restoration efforts. Reef restoration costs are generally lower when performed at larger scales (Hughes *et al.* 2023).
3. The dramatic increase in synergistic stressors on corals- and notably the interaction of ocean warming with other factors- is the primary threat to the long-term persistence of coral reefs.

   Efforts should therefore integrate methods to maximize genetic diversity and facilitate assisted evolution to ensure increased resilience in the restored community.
4. Coral outplanting cost-effectiveness is a major bottleneck to restoration at scale.

   Innovative strategies are needed to improve attachment methods and materials, as well as optimize deployment times (e.g., via automation). Tools are needed to enable different methods (from production to deployment) to be compared against goals, and to help identify where improvements must be made.
5. Long-term holistic monitoring is vital to track success and guide whether and where activities should scale, continue as is, or stop (i.e., dynamic decision-making). Integrated systems are required that include monitoring environmental parameters, operations (including LSS), outplant performance, and ecological responses, while generating informative datasets to optimize workflows and continually upscale. Transitioning to computer-aided data collection and analysis requires well-established and tested workflows and data architecture.

Applications should be assessed against the following criteria to assess their potential to be disruptive technologies/solutions:

Lead time: Time to be market-ready for widespread adoption and supply.

Quality: Potential of the technology to restore/enhance reproductive activity/ output of coral populations and to promote genetic diversity and resilience.

Cost: The amount of estimated R&D funding that would be needed to develop solutions so that the underlying technology can be widely adopted.

Flexibility: Potential to upscale under a variety of environmental conditions and economic contexts.

While lower technical requirements generally make ocean-based coral propagation cheaper (and cost-effective for corals propagated asexually under reef-relevant environmental regimes), coral aquaculture in land-based nurseries:

1. Offers a controlled environment,
2. Enables easier pathways for sexual propagation and securement of brooding stocks, and,
3. Has greater potential to benefit from automatization. Many technologies that could be used to advance coral aquaculture to industrial scales are already used in the fish aquaculture and aquarium trade industries, yet they are not often applied in synergy to increase efficiencies and scalability of coral aquaculture. A major deficit identified is the lack of standardization of tools and approaches.

Other obstacles also hinder the scale and effectiveness of current restoration endeavors. One is insufficient exchange of technical knowledge among practitioners and with other, related industries.

Although there are numerous ways to improve aquaculture efficiency, either through existing solutions or by adapting techniques from other fields, there is still a lack of strategic deployment and integration of these approaches. For example, leveraging technologies and methods from mariculture and the aquarium trade may significantly advance the efficiency of coral restoration.

Another important outcome is the adoption of reef restoration technologies that are already at technology readiness level 9 (TRL9) but lack widespread implementation, for example, due to lack of an effective supply chain. Such “ready-to-scale” technologies require attention and promotion- through suitable business and commerce platforms- to achieve their full potential.

To promote technology transfer, establishment with cross-disciplinary working groups (such as the Coral Restoration Consortium), as well as partnering with CORDAP and other organizations is crucial. Bringing together representatives from the aquarium trade, other aquaculture sectors, engineers, and coral restoration practitioners is similarly critical to foster collaboration and optimize knowledge exchange.

Roadmap for R&D

Credit: KAUST Coral Restoration Initiative

2.1 Preamble

This in-person workshop held from the 29th to 31st of January 2023 at KAUST, Saudi Arabia brought together academic, industry-based, and technology experts from various fields, including scientists in coral reef ecology alongside experts in marine restoration, engineering, and aquaculture. The workshop aimed to promote interdisciplinary dialogue among participants to identify areas where investments in R&D are needed to enable economical coral aquaculture and outplanting at scale. In particular, the workshop aimed to identify and discuss new strategies for technology-enabled coral aquaculture, monitoring, and outplanting at industrial scales.

2.2 Introduction

Background

Anthropogenic impacts have led to an unprecedented decline in coral reefs worldwide (Hughes *et al.* 2017), with further deterioration predicted by the end of this century mostly driven by unavoidable climate change (Bindoff *et al.* 2019, Bove *et al.* 2022).

Indeed, climate change has led to approximately 4 to 7% coral cover loss compared to historical levels, primarily due to the increased frequency and severity of high temperature-induced coral bleaching events (Souter *et al.* 2020, Tebbett *et al.* 2023).

The realized and projected impacts are at odds with the goal of the Kunming-Montreal Global Biodiversity Framework to halt further loss and to actively restore 30% of degraded ecosystems by 2030.

Scientists are calling for preservation and enhancement of reefs, particularly in climate refuges, as a means of addressing global declines in coral reef health (Hoegh-Guldberg *et al.* 2023).

Addressing this conundrum requires that efforts focus on concurrently removing pressures, including mitigating climate change to the maximum possible ambition, while restoring coral reefs at scale to ensure they continue to support marine biodiversity and provide valuable ecosystem services.

The challenges facing coral reef restoration

Active and innovative coral reef management methods are currently being explored (van Oppen *et al.* 2015, Anthony *et al.* 2017, Damjanovic *et al.* 2017, van Oppen *et al.* 2017, National Academies of Sciences 2019), propelled by large R&D initiatives (e.g., Bay *et al.* 2023), such as Australia's Reef Restoration and Adaption Program (RRAP) and CORDAP. However, identifying economically viable approaches to restore and enhance coral reef areas at scale remains challenging, and cost-effective solutions for doing so lag behind those of terrestrial systems and even other coastal habitats, such as mangroves and saltmarshes (Duarte *et al.* 2020).

Although coral restoration efforts are advancing rapidly, they mostly remain limited to small projects (<1 km^2; Boström-Einarsson *et al.* 2020, Ferse *et al.*

2021). In contrast, mangrove restoration projects have already exceeded thousands of km^2 in places like the Mekong Delta. Innovative and industrial-scale approaches are required to realize cost-effective, large-scale coral restoration (Schmidt-Roach *et al.* 2020).

Such efforts should bring coral production to a scale at which diverse and resilient coral populations are established (e.g., Randall *et al.* 2020), thus achieving meaningful ecological outcomes (Vardi *et al.* 2021, Blanco-Pimentel *et al.* 2022, Montano *et al.* 2022).

Economic considerations

Coral reef restoration ranks amongst the most expensive types of marine and coastal habitat restoration, with an estimated median cost of $404,147 USD per hectare (at base year 2010; Bayraktarov *et al.* 2019).

Median project sizes range from 100m^2 to 500m^2, and scaling up production does not necessarily result in proportionate cost savings (Bayraktarov *et al.* 2016, but see Hughes *et al.* 2023).

A global median cost per outplanted coral of approximately $10USD or ~$400,000USD per hectare (Bayraktarov *et al.* 2019) currently prohibits coral restoration at scale. Similarly, Hughes *et al.* (2023) calculated a cost range of $50,000 to $1 million USD per hectare. The high cost is due in part to the labor-intensive nature of the restoration process and its dependance on expensive marine and underwater operations.

However, too few restoration projects have been conducted to date at large enough scales to truly understand the cost. Indeed, linear extrapolation of cost across scales is unreasonable, as economies of scale may be gained, including benefiting from learning curves. Regardless, achieving restoration at the scales needed requires more efficient and effective pathways.

Higher efficiency may be achieved via development of industrial-scale facilities and implementation of industrial workflows for coral production and transplantation, inspired by models existing in agriculture, which could significantly increase the speed and scale of restoration efforts (Suzuki *et al.* 2020, Lippmann *et al.* 2023, Schmidt-Roach *et al.* 2023).

Automation, robotics, and machine-learning, where applicable, may play a major role in improving efficiency, reducing costs, and increasing the number of corals that can be produced and transplanted (Morand *et al.* 2020).

For example, many projects still apply outplanting techniques that are associated with considerable time investments (e.g., several minutes), such as cement or epoxy putty-based outplanting (Toh *et al.* 2017, Unsworth *et al.* 2021); moving to quicker techniques, such as nail-based solutions (Suggett *et al.* 2020; Schmidt-Roach *et al.* 2023) could significantly reduce the cost per coral outplant (>50% savings).

Considering that most coral reefs occur in low-income nations, practical, low-tech solutions may provide the most viable options there (Bayraktorov *et al.* 2020). This is a particularly important consideration, as robotized solutions could create less employment and social benefits than approaches that rely more heavily on human labor.

Some degree of automation, involving simple systems that can be produced in low-income economies, may underpin restoration at scale across all economic contexts.

The parallel with aquaculture is relevant, as industrial aquaculture (i.e., producing algae and animals at scale) features a mix of sophisticated and low-tech components that have successfully been established in low-income nations; a similar approach could be taken with coral gardening.

For instance, SCUBA diving operations remain expensive because of the cost and maintenance of equipment, as well as personnel time (not to mention risks). At similar costs, automated land-based operations could help reduce diving time.

Many projects still evaluate success in terms of the number of corals outplanted, while neglecting to account for the long-term survival rates of outplanted corals and more robust metrics of ecosystem performance.

Coral restoration projects have reported impressive short-term survival rates of outplants (61%, Bayraktarov *et al.* 2019), though outplant monitoring is often limited to one year (Böstrom-Einarsson *et al.* 2020).

Indeed, long-term survival is often significantly lower, with rates seven years post-outplanting in Florida estimated at <10% (Epstein *et al.* 2001). Although transplanted corals, even those sexually produced, have been observed to spawn (Quiroz *et al.* 2023), few projects monitor reproduction and its contribution to the increase in coral abundance post-transplantation. Monitoring programs needed to collect these ecosystem-scale data are often prohibited by their high costs.

Advancements in coral propagation techniques

Scleractinian corals exhibit a remarkable array of life history strategies, capable of both sexual and asexual reproduction. Species vary in their reproductive methods, with some engaging in internal fertilization or brooding, and others in broadcast spawning, where eggs and sperm are released into the water column (Harrison 2011).

These life histories have practical implications for coral propagation in both land-based and marine nurseries. Regardless of the mode of reproduction, coral restoration efforts typically depend on the ability to produce corals cost-effectively at scale. The goal should be to nurture corals to a size where their chances of survival post-transplantation are significantly higher (Edwards 2010, Ligson *et al.* 2022, Guest *et al.* 2023); this can be achieved in either land-based or marine nurseries (Barton *et al.* 2017).

Fragments can be collected from donor colonies for clonal (Chou *et al.* 2009, 2016) or sexual propagation. As coral fragments or recruits reach a larger size, they can be further fragmented, effectively amplifying the number of fragments available for outplanting to reefs while avoiding impacts to the coral stock (Soong *et al.* 2003). Clonal fragmentation, due to its straightforward nature, is the predominant method employed for restoration activities (~70% of projects; Boström-Einarsson *et al.* 2020).

Although it comes at the cost of reduced genetic diversity compared to sexual propagation, this approach is advantageous because it avoids issues commonly observed in the life histories of many hard coral species, such as high mortality rates of larvae post-settlement and slow growth rates (Rinkevich *et al.* 2014, but see Guest *et al.* 2023).

Coral fragments can be gathered opportunistically from broken corals- so called "corals (or fragments) of opportunity"- or carefully extracted from donor corals using bone cutters, wire cutters, or hammer and chisel (Young *et al.* 2020).

Larger fragments are preferred due to their higher survival rates, but removing them from donor corals can be harmful (Taira *et al.* 2017). As such, it is generally recommended that <10% of a donor colony is harvested to supply material for restoration (Epstein *et al.* 2001).

To increase the growth of fragments, a process called "micro-fragmentation" may be employed (Forsman *et al.* 2015, Lirman and Schopmeyer 2016). Originally explored and practiced in land-based nursery facilities, this technique has also been shown to be effective via direct outplanting (Tortolero-Langarica *et al.* 2020).

Credit: KAUST Coral Restoration Initiative

Recent developments in micro-fragmentation have led to significant advancements in coral restoration (Forsman *et al.* 2015). By cutting multiple small (1 cm^2) fragments using a diamond saw and placing them in close proximity, growth rates, especially for massive species, can be increased by up to 10-fold (Tortolero-Langarica *et al.* 2020).

Small colonies invest heavily in growth to gain area and secure space, making this approach particularly successful in quickly propagating colonies of slow-growing, massive corals (Sam *et al.* 2021).

Assays involving micro-fragmentation can also be employed to evaluate the performance of coral propagation based on fragment size and local ecology and oceanography, thereby enhancing the effectiveness of active coral reef restoration (Knapp *et al.* 2022).

Incorporating an intermediate nursery (grow-out) phase, often referred to as the "coral gardening" stage, may enhance survival rates of coral outplants (de la Cruz *et al.* 2014, Afiq-Rosli *et al.* 2017). Executed both onshore within aquaculture tanks and in oceanic environments, this phase permits the nurture of smaller fragments and the creation of stocks to reduce wild harvests.

Although coral gardening is amongst the most commonly practiced approaches, a recent evaluation by Australian scientists determined that it does not represent a financially viable or expandable solution (Bay *et al.* 2019) for reaching ecologically relevant scales, since these approaches demand long time periods for implementation (Hughes *et al.* 2023).

Indeed, if outplanting efforts are evaluated by area covered, they become impractical due to the large number of colonies required to restore at regional scales. More strategic and informed outplanting to restore/enhance reproductive activity *in situ* via, for example, coral spawning hubs (Schmidt-Roach *et al.* 2020, 2023), can justify coral gardening efforts both ecologically and economically.

Integrating sexual reproduction into coral propagation programs can significantly enhance genetic and phenotypic diversity and minimize the harvest pressure on wild populations (Baums *et al.* 2019). As sexual propagation allows the generation of millions of larvae that can be directly or indirectly (via recruitment to settlement substrates) seeded to reefs without a prolonged gardening phase, Bay *et al.* (2019) deemed this strategy more economical. Yet, sexual propagation is currently only accounted for in a small number of coral restoration projects (Boström-Einarsson *et al.* 2020), likely due to the challenges associated with larval rearing and the successful recruitment of different species.

Species-specific larval behavior, particularly in terms of settlement timing and substrate preference, further complicates these efforts (Randall *et al.* 2020). Acroporids, which are commonly used in scientific studies, have been a primary focus for restoration efforts that prioritize sexual reproduction (Baria *et al.* 2012, Baums *et al.* 2019).

Credit: KAUST Coral Restoration Initiative —

Methodological approach of the workshop

The workshop's participants were assigned the task of investigating the technological developments necessary for enhancing coral reef restoration on a scale that would make a significant ecological difference. They were asked to identify and assess (rate) three categories of solutions (Supplementary table 1):

a. Innovative approaches for developing land- and ocean-based coral nurseries,

b. Methods for incorporating and executing assisted evolution strategies,

c. Technological means of transplanting and monitoring corals.

Our evaluation system incorporated factors like TRL, scalability, development and application costs, and potential impact (Supplementary Table 2). The experts' assessments were then scrutinized and scored based on four key elements:

1. Lead time
2. Quality
3. Cost
4. Flexibility

These ratings (see Methods and Supplementary tables within Appendix) were designed to gauge the capacity of each solution to enable effective and efficient large-scale reef restoration across various ecological conditions and resource availability.

This process aimed to pinpoint vital and urgent areas that would greatly benefit from focused investments, thereby rapidly enhancing reef restoration methods at a broader scale. The following discussion is guided by these ratings and focuses on the most highly scored topics.

Regardless of the mode of reproduction, coral restoration efforts depend on our ability to produce corals cost-effectively at scale.

The goal is to nurture corals to a size where their chances of survival post-transplantation are significantly higher (Ligson *et al.* 2022), and this can be achieved in either marine or land-based nurseries.

These facilities differ largely in their infrastructure requirements and level of implemented control.

Credit: KAUST Coral Restoration Initiative

2.3 Towards industrial coral production

Coral propagation on land in aquaculture systems can reduce marine operations, providing easy access to and protection of stocks. This is in part due to the fact that *ex situ* coral culture practices in land-based setups benefit from the wealth of knowledge derived from experiences acquired in the coral aquarium industry, offering various options that can be adopted, optimized, and potentially scaled up (Leal *et al.* 2016).

Their controlled environments may permit optimizing growth with the adjustments of lights, currents, and feeding regimes (Huang *et al.* 2020). However, it should be noted that acclimation to nursery conditions has been reported to alter the biology and physiology of corals, even when raised under natural light (Gantt *et al.* 2023).

The large-scale seed industry beginning with crop-breeding and ending with seed distribution can provide examples of infrastructure and workflows that can potentially be adapted to land-based coral aquaculture. Particularly, native seed supply chains for terrestrial restoration (Cross *et al.* 2020) offer insight into how to work with sensitive species, such as corals, which require optimization to increase survival at different stages of the production chain.

Indeed, land-based coral nurseries could serve as living genetic repositories (Schopmeyer *et al.* 2012, Zoccola *et al.* 2020), providing convenient access to the cultured organisms and even playing a role in savaging restoration efforts after catastrophic events. For instance, the extended heat wave that affected Florida in the summer of 2023 threatened both natural corals and those in nurseries, and a major effort was made to relocate corals to land-based facilities, which provided a refugia until conditions were suitable again for coral survival.

Establishing coral aquaculture facilities comes with significant financial and infrastructural demands, making them expensive and challenging to scale. The largest such facility under construction in Saudi Arabia aims to produce approximately 400,000 coral fragments annually, which is a small quantity when considering numbers required for ecosystem-wide restoration (Hughes *et al.* 2023).

Despite these limitations, the critical role these facilities play in conserving and propagating coral species in highly controlled environments highlights their invaluable contribution to marine conservation, justifying their establishment and operational costs.

Nevertheless, adopting hybrid models that combine

Table 1. Categories and technical status of current land-based coral aquaculture facilities. LSS = Life Support System

Category	Technology	LSS	Example(s)	Example function
Hobbyist aquaria	Off-the-shelf and custom design	Closed	Multiple aquarium industry solutions	Personal entertainment with ornamental corals
Aquarium trade coral farms	Off-the-shelf and custom designs	Mostly closed with some semi-open or open	whitecorals.com marine-farmers.com faunamarincorals.de coralmorphologic.com	Personal entertainment with ornamental corals exhibiting specific features, origin often unknown
Public aquaria	Custom design	All types	ReefHQ (Australia) BurgersZoo (Holland) Mote Aquarium (USA) Chimelong Spaceship (China) Horniman Museum (UK)	Ornamental corals for public education/ entertainment, origin often unknown. Movement by some to preserve corals.
Research facilities	Custom design	Mostly semi-open or open with some closed	AIMS SeaSim (Australia) KAUST Coastal and Marine Resources (Saudi Arabia)	Research
Coral restoration farms	Custom design	Mostly semi-open or open with some closed	Mote Marine Lab (USA) Coral Vita (Bahamas) KRRI (Saudi Arabia) Center for Marine Innovation (Dominican Republic)	Restoration

Table 2. Some of the largest coral farms.

Name	Location	Capacity and diversity
Mote Marine Laboratory	Summerland Key, Florida	34,400 coral fragments of 17 species
Coral Vita	Nassau, Bahamas	30,000 coral fragments of 24 species, with additional facilities for sexual propagation and settlement
KCRI	NEOM, Saudi Arabia	20,000 in development nursery
Australia	AIMS, Townsville (QLD) and satellite production units	500,000 in primary nursery to be established by late 2024

smaller, land-based operations with ocean-based nurseries could present a viable solution to mitigate infrastructure expenses. This strategy leverages the strengths of both approaches, optimizing resource allocation while expanding the capacity for coral propagation and conservation, thereby potentially offering a more cost effective approach to sustaining coral ecosystems.

Current coral aquaculture systems can be separated into five main categories (Table 1), with some of the largest systems currently operated in the Caribbean, Australia, and Saudi Arabia (Table 2).

Controlled environments on land

Coral aquaculture in *ex situ* nurseries offers a controlled environment for coral growth and facilitates research to optimize coral husbandry techniques.

Recent technological advances have improved the infrastructure, LSS, and tanks necessary for successful coral cultivation. In addition, industrial workflows, such as tracking and monitoring, can now be automated using control systems, robotics, and sensors.

Land-based coral aquaculture systems can be closed or open seawater systems or provide the flexibility to be run in both modes. The difference lies in their rates of water turnover, which impacts water quality and biosecurity.

Closed systems with no direct water replacement from the sea offer more precise control, reduced risk of contamination, and the ability to maintain stable conditions. However, they require more sophisticated filtration systems, a regular supply with fresh seawater (naturally sourced or artificially produced), and other technical controls.

On the other hand, open seawater systems source their seawater via pipelines from nearby sources. While this permits less control over water quality, it reduces costs and technical effort. However, depending on the location of the nursery, it should be noted that the establishment and maintenance of seawater supply plumbing can pose a significant technical effort and cost.

LSS and infrastructure

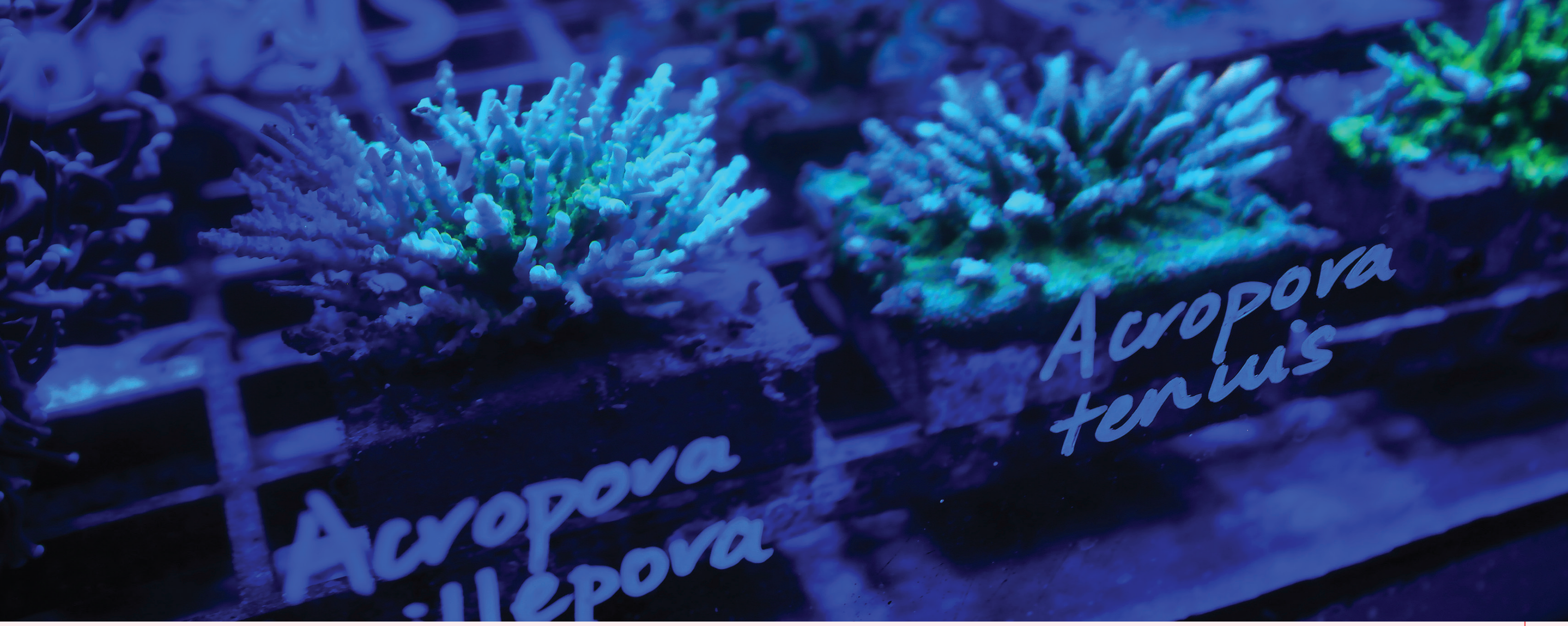
Regardless of the system type, advanced LSS are vital to realize stable and suitable conditions for corals. The LSS of a coral aquaculture facility is a critical piece of infrastructure designed to mimic a natural optimal environment for corals and maintain the required conditions for their growth and survival. It typically consists of several components working together to regulate water quality and provide essential elements for coral health.

LSS consist of nested infrastructures featuring an overarching layer controlling the overall environmental parameters, specifically water supply to the tanks, and tank-specific controls on light, flow, and other seawater quality parameters.

Storage tanks are often used to adjust the water temperature (heating/cooling elements such as heat exchange) and salinity (additional reverse-osmosis [RO]/deionized water [DI] reservoirs for adjustments), as well as remove unwanted impurities (e.g., via mechanical, chemical, and/or biological filtration). Chemical treatment may be used to adjust seawater chemistry, such as calcium and carbonate supplements to replace the quantities uptaken by the corals and other calcifying organisms (e.g., crustose coralline algae).

Further water treatment may include UV sterilizers, ozone exposure, and protein skimmers (to remove particles). Tank-specific conditions are realized with current/wave pumps and different lighting systems (Liu *et al.* 2020).

Land-based nurseries require infrastructure similar to those in aquaculture hatchery facilities, where either open or closed-circuit seawater supply systems are



Credit: Australian Institute of Marine Science | Marie Roman

combined with the capacity to control environmental conditions in the tanks. These are in operation in many low-income countries, suggesting there is no major technological or capacity gap to deploy them across nations, shall funding be available.

In any case, the level of sophistication can be reduced greatly while still supporting coral production for outplanting. For instance, for five years we have maintained at KAUST flow-through, open-air tanks with no tank-level LSS other than simple shading using mosquito nets and a stable supply of filtered, temperature-adjusted seawater into the flow-through tanks. Tanks can also be constructed from inexpensive materials, such as cattle water troughs, that are widely available in many regions.

Ocean-based coral culture

Compared to their land-based counterparts, *in situ* nurseries require less infrastructure and specialized equipment, translating into lower costs and energy requirements.

Hence, *in situ* nurseries are the most widely used method for coral propagation globally (Boström-Einarsson *et al.* 2020).

A spectrum of ocean-based coral farming methods has been developed, spanning simple, rope and metal grid nurseries (Amar & Rinkevich 2007, Levy *et al.* 2010, Hernández-Delgado *et al.* 2014, Lohr *et al.* 2015) to more intricate designs like the "Coral Tree Nursery" (Nedimyer *et al.* 2011). The latter, which resembles an antenna, is often constructed from PVC pipes or similar materials.

Each type of *in situ* nursery offers unique advantages in terms of cost, scalability, and suitability for different coral species or locations. For instance, rope nurseries or coral nursery trees are particularly effective for branching species (Levy *et al.* 2010, Dehnert *et al.* 2022), while table nurseries seem favorable for the growth of massive and tabulate coral forms (Shaish *et al.* 2008, Poquita-Du *et al.* 2017).

Nurseries may be placed on the substrate or suspended in the water column. Suspended nurseries also offer the benefit of reducing the damaging effects of waves thanks to their ability to move within the water column (Rinkevich 1995, Howlett *et al.* 2021).

The establishment and maintenance of *in situ* nurseries involve varying costs, significantly influenced by the frequency of cleaning, the materials used, and labor costs (e.g., Bayraktorov *et al.* 2019).

Consistent maintenance, including cleaning and monitoring coral health, is vital for ensuring decent survival rates (Goergen *et al.* 2020), which is closely related to local conditions like levels of pollution and herbivory. *In situ* nurseries (in some regions) face challenges in sourcing sufficient coral stock and managing labor-intensive operations.

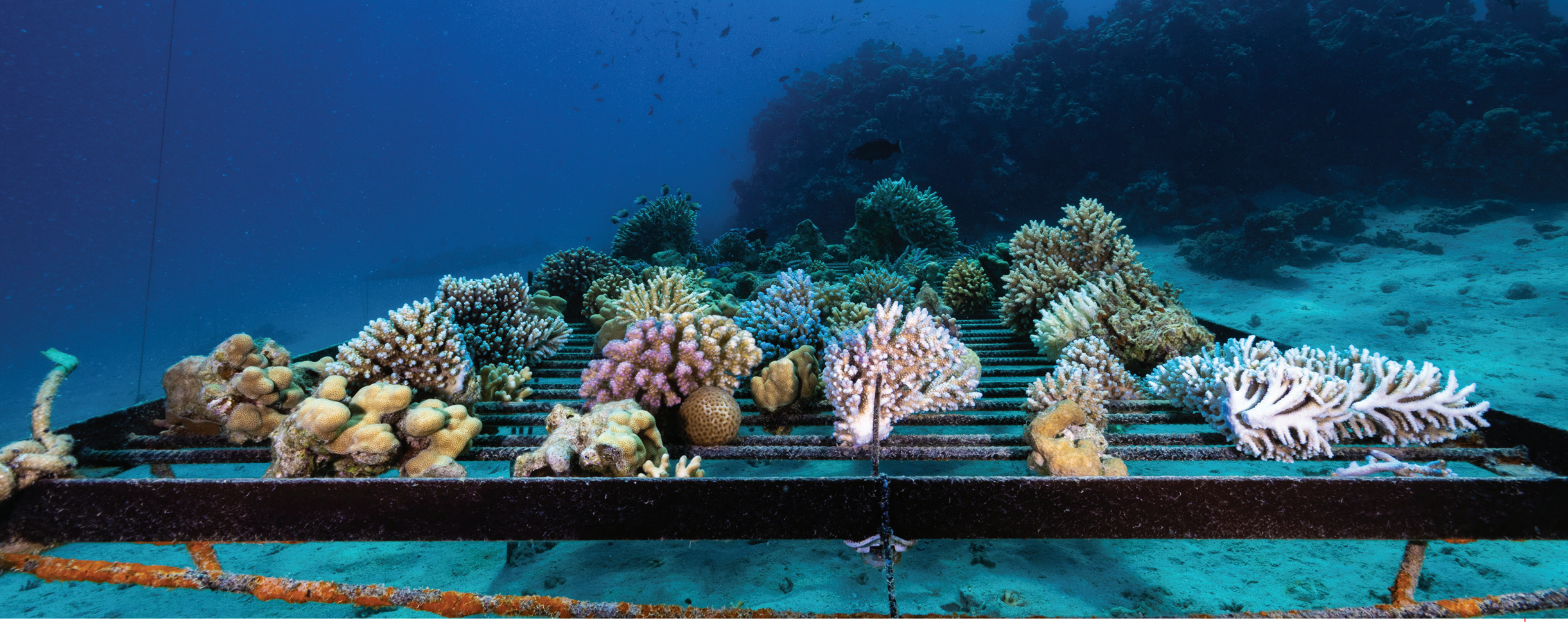
Some projects have successfully integrated these nurseries with community initiatives, involving local divers and fishermen, thereby enhancing socio-environmental benefits while reducing costs (Hernández-Delgado *et al.* 2014, Todinanahary *et al.* 2017, Ter Hofstede *et al.* 2019, Howlett *et al.* 2022).

R&D efforts required to bring coral nurseries to the aquaculture scale

To enhance coral production effectively, it is essential to balance operational costs with productivity driven by aquaculture technologies that support the growth and survival of nursery-reared corals.

We identified three priority areas that should be improved through R&D efforts:

1. Standardization and modularization of infrastructure
2. Reduction of maintenance and cleaning
3. Technical solutions for the enhancement of coral growth, performance, and survival



Credit: KAUST Coral Restoration Initiative

Priority area 1a: Standardization of tools and substrata

In coral aquaculture, a variety of tools are commonly used to fragment corals and attach them to substrates, which are typically made of ceramic, cement, or plastic.

Many terrestrial aquaculture setups prefer using tiles or plugs commonly found in aquarium stores, which are usually set on raised grids (e.g., egg crates) to keep them elevated from the bottom and prevent sediment accumulation (Leal *et al.* 2014). Ensuring a firm attachment is crucial for facilitating the coral's natural self-adhesion, where its tissue and skeleton expand onto the substrate; this process is species-dependent and can span weeks to months (Guest *et al.* 2011).

A variety of adhesives are currently used to attach corals to substrates, including epoxies, cyanoacrylate gels (Dizon *et al.* 2008), and cement (Unsworth *et al.* 2021); non-chemical means (e.g., nails and clamps) may also be used (Suggett *et al.* 2020).

UV-curable, oligomer-based adhesives have also been explored (Takeuchi *et al.* 2019), and a peptide hydrogel recently showed promise for fast underwater attachment (Moretti *et al.* 2023). Given their crucial role in coral restoration, research into cheap, non-toxic adhesives could significantly advance the field. Novel substrates, such as carbon-negative concrete (e.g., Partanna, Bahamas), are currently being explored to provide frameworks for coral attachment in restoration projects conducted in areas where the existing coral habitat is degraded. Such substrates may be treated to foster coral growth, using coral-friendly antifouling chemicals that inhibit the growth of competing organisms. Furthermore, 3D-printing may assist in creating substrates (Berman *et al.* 2023), which can, for instance, mimic coral shapes as bases for micro-fragmentation (Albalawi *et al.* 2021).

Schmidt-Roach *et al.* (2023) suggested a standardized and holistic modular system for coral farming and outplanting, known as Maritechture™. The system uses screwable tiles as the basis for coral attachment, and these tiles can be easily detached and re-attached as needed.

Complimentary crates are used as a platform to upscale coral farming. The crates are stackable and securely clipped together. Surface areas are minimized to reduce cleaning efforts and accelerate workflows. Such modularity has the potential to significantly streamline coral husbandry workflows and facilitate direct deployment onto natural or artificial reefs. The tiles can be equipped with microchips to allow tracking and detailed monitoring. Different designs have been created for fragmentation, micro-fragmentation, and sexual recruitment.

Priority area 1b: Reduction of maintenance and cleaning

Maintenance and cleaning of both ocean and land-based nurseries represent a major burden in coral restoration workflows, with significant gains in cost reduction possible if the balance between cleaning frequency and coral health is optimized.

Purpose-built infrastructure to grow corals should minimize surface area to reduce algal and microbial growth. Near-future technologies include the development of environmentally friendly antifouling coatings and biological controls, which would be particularly advantageous for *in situ* nurseries, where access to site can be a major impediment (Tebben *et al.* 2014).

These innovations aim to reduce the need for manual cleaning, thereby ensuring coral health while lowering maintenance costs through, for instance, exploring substrates or coatings that prevent growth from fouling organisms. To date antifouling coatings have been researched primarily in the maritime industry, but antifouling agents can be toxic to marine organisms (de Campos *et al.* 2022). For instance, the use of antifouling chemicals in coral nurseries, although effective in reducing cover of biofoulants by 90%, has also been found to cause coral mortality (Shafir *et al.* 2009). Accordingly, there is a need to identify antifouling materials/substances that are coral-friendly (Ferreira *et al.* 2021).

Researchers are studying encapsulated nanoengineered substrates with antifouling characteristics; these have shown promising results, successfully inhibiting macroalgal growth with no detrimental effects on coral larvae (Roepke *et al.* 2022). However, these are currently only designed for laboratory-use, requiring further field-testing prior to more widespread adoption.

The integration of robotics in the maintenance of coral tanks could be a significant benefit for land-based nurseries. Such robots would need to navigate the tank systematically, ensuring thorough cleaning while avoiding impacts to the corals; this could be realized via advanced, AI-driven monitoring technologies. The AI could be trained to focus on, for instance, areas of highest algal growth, and this capacity would be especially advantageous in large-scale operations where manual cleaning is impractical. The development of these cleaning robots may also offer commercial opportunities in the public aquaria sector, where cleaning and maintenance also contribute greatly to costs.

Land-based nurseries permit the co-culture of beneficial biota like fish, clams, crabs, and sea cucumbers, which assist in controlling the proliferation of algae (Craggs *et al.* 2017, Henry *et al.* 2019) and pests. Co-culture tanks with both snails and urchins require one-third the manual cleaning workload as those without them (Neil *et al.* 2024). Designing the optimal co-culture community requires knowledge of coral reef community interactions and dynamics (Liu *et al.* 2009).

Priority area 1c: Technical solutions for the enhancement of coral growth, performance, and survival

Providing environmental conditions suitable to support coral growth and overall health (Dennison and Barnes 1988, Ferrier-Pagès *et al.* 2003, Slagel *et al.* 2021) is essential to successful coral nursery operations.

The primary challenge lies in identifying and maintaining the optimal conditions for each coral species, as critical factors such as optimum temperature can vary significantly from one to another (Merck *et al.* 2022).

Light is a key factor for coral growth, with corals deriving benefits via their symbiotic algae (Table 3). Research by Izumi *et al.* (2023) demonstrated that coral growth is more pronounced with extended light exposure and increased intensity across various species. However, not all species show significant growth benefits from altered light spectra, and high-light conditions do not universally enhance growth (Rocha *et al.* 2013).

Given the very modest calcification enhancements (<0.2% per day) delivered by artificial light over natural light documented by Slagel *et al.* (2021), the costs and energy consumption of artificial lighting in coral restoration warrant careful consideration. That said, coral recruits exhibit increased growth under blue-shifted LED spectra compared to natural light (Ponce 2023), indicating that benefits may be life history stage-specific.

Maintaining temperatures within an optimal range of a coral's native environment is crucial to avoid stress and promote growth, unless the goal is to elevate thermo-tolerance (e.g., Putnam *et al.* 2017). Merck *et al.* (2022) emphasized that different coral species have unique temperature preferences, particularly in controlled environments, with growth variations up to 1% per day. While technical solutions like heating or cooling systems exist, they can be energy intensive. Hence, adaptive management strategies may be more cost-effective (Schmidt-Roach *et al.* 2020, 2023). For example, seasonal farming, whereby coral species that perform better under colder conditions may be targeted for propagation in winter, should perhaps be more widely adopted.

Laboratory experiments with *Acropora tenuis* have demonstrated that blue light enhances bleaching tolerance (Gong *et al.* 2023), indicating that light spectrum adjustments may modulate temperature stress responses and, in the context of coral aquaculture, permit lower cooling requirements.

Furthermore, the interaction between temperature and light affects competing organisms like turf and macroalgae, which can impact coral growth. Mesocosm experiments can be conducted to optimize light levels to where coral health is maximized at an acceptable level of growth of key coral competitors (Liu *et al.* 2009).

Nutritional enhancement significantly boosts growth and survival in juvenile corals. Toh *et al.* (2014) reported increases in survival rates by up to 25% and growth by up to 90% over 24 weeks post-transplantation. Additionally, Huffmyer *et al.* (2021) found that feeding enhances temperature tolerance in juvenile corals, and Huang *et al.* (2020) showed significant growth increases in response to feeding in adult corals, as well. Further, some supplements, such as natural antioxidants, can also improve coral thermal stress performance of both fragments and outplants (Contardi *et al.* 2023).

Mineral accretion technologies like Biorock have been suggested to increase coral growth and survival, but the empirical evidence is inconclusive. While Sabater *et al.* (2002, 2004) observed positive effects on growth and survival, other studies present varied outcomes. Some reports claim benefits (Goreau 2014, Goreau and Prong 2017, Sineau and Blouki 2020), while Romatzki (2014) noted partial negative effects, and Cook *et al.* (2023) found no significant differences compared to controls.

In conclusion, while the aforementioned studies suggest a variety of strategies to enhance growth and performance, close monitoring and adaptive management are likely required to optimize production of industrial-scale operations, and not all coral species will have the same requirements (see Table 4).

Public resources such as the Coral Trait Database (Madin *et al.* 2016), which curates 56 traits for 1,547 coral species (as of mid-2024), could be mirrored to contain husbandry information, guiding practitioners to improve yields and reduce costs.

Table 3. Various coral treatments and their impacts on growth/size.

Treatment	Growth metric	% increase per day	Reference
Feeding	Skeletal density	0.50 - 0.84%	Ferrier-Pages *et al.* 2003
High vs. low light	Skeletal density	Up to 0.43%	Ferrier-Pages *et al.* 2003
Feeding and light	Specific growth rate	0.8%	Huang *et al.* 2020
Artificial light (LED) vs. natural	Calcification	0.13%	Slagel *et al.* 2020
Artificial light (LED) vs. natural	Linear extension	No significant difference	Slagel *et al.* 2020
Current regime: Stirred vs. unstirred	Dark calcification	59%	Dennison and Barnes 1987
Extended photoperiod	Weight	No significant benefit under high light conditions	Izumi *et al.* 2023
Light spectra	Weight	> 0.1% benefit for some species	Izumi *et al.* 2023
Temperature (25.2 °C vs. 29.5 °C)	Area	Up to 1%	Merck *et al.* 2022
Ex situ nutritional supplementation	Volumetric growth	Up to 0.05%	Toh *et al.* 2014

Table 4. Recommendations for technology advancements for coral production infrastructure.

Priority area	Topic	Technology	State-of-the-art and current limitations	Features	Impact
1a	Standardization	Mobile/modular land-based facilities	Prototype stage	Low infrastructure requirements: pipes, power, seawater	Quick establishment of temporary land-based nurseries providing flexibility and adaptability
		Mobile/modular ocean-based facilities	Prototype stage	Flexibility to respond to altering environmental conditions (shading, relocation, warning sensors)	Quick establishment of ocean-based nurseries providing flexibility and adaptability
		Tools	Some available	Faster implementation and easier handling	Reduced costs due to higher efficiency
1b	Reduction of maintenance and cleaning efforts	Coral-friendly antifouling coatings/ materials	Some non-biocidal options are available, but further coral-targeted formulations are needed	Suitable and lasting antifouling coatings to reduce cleaning efforts	Reduced cleaning efforts, potentially easy and universal application
		Mechanical cleaning	Ongoing research	Automated robotics	Warehouse-style robotics that automatically assess need and execute efficient cleaning across tanks
		Biological cleaning	Prototyping phase, slow, not scalable, and per-tank level	Effective co/ poly-culture	Significant reduction of husbandry efforts
1c	Technical solutions for the enhancement of coral growth, performance, and survival	Improved light regime	Proven and applied at scale	Optimized conditions	Increased growth and performance
		Temperature, and flow regime systems, materials science for coral substrates, tank space optimization	Proven and applied at scale		
		Feeding	Proven and applied at scale		

Credit: Austrailan Institute of Marine Science | Marie Roman

2.4 Management and workflows

R&D efforts required to improve coral nursery management and workflows

One of the most significant challenges in the quest to scale up coral restoration lies in the substantial time and labor investment demanded along the entire production pipeline (Figure 1), primarily attributed to the time-intensive maintenance of coral stocks and inventory. This maintenance plays a pivotal role in ensuring the health and vitality of the corals at various stages of growth and development.

From land-based to *in situ* nurseries, the seamless integration of workflows becomes paramount in achieving the desired scale for ecologically relevant outcomes (Table 5). Achieving efficient workflows requires:

1. Livestock management
2. Efficient larval propagation
3. Standardized software
4. Simulations for improved decision-making

Priority Area 2a: Livestock management

Efficiently managing and tracking inventory in coral restoration efforts facilitates the systematic collection of data on the successes and failures throughout the restoration process. These data are an invaluable resource, enabling researchers and practitioners to fine-tune restoration techniques for different coral species and growth forms.

By identifying what works best, and refining methodologies, restoration practitioners can enhance the overall effectiveness of their restoration initiatives.

Additionally, meticulous inventory management allows tracking of species, genotypes, and phenotypes, which is essential for ensuring the conservation of genetic diversity within coral populations. It also helps identify specimens with beneficial traits that can contribute to more resilient coral communities better equipped to thrive in challenging environments.

Furthermore, efficient inventory management supports logistical planning and resource allocation (Hernández-Delgado *et al.* 2018). This ensures that the necessary supplies and equipment are available when needed, reducing delays and maximizing productivity.

The principles and technologies from precision aquaculture (Antonucci and Costa 2020) can be effectively applied to coral restoration. Data-driven decision-making, fueled by advanced techniques like machine-learning, will be instrumental in optimizing inventory management. For instance, integrating current techniques like RFID chips for tracking with machine-learning could streamline inventory management, enhance efficiency, and help provide data for decision-making, including tracking growth, diseases, and readiness for outplanting (Schmidt-Roach *et al.* 2020).

These advancements herald a promising future for coral restoration. The integration of these tools and technologies can allow for real-time monitoring, empowering restoration practitioners to monitor genetic diversity and identify advantageous traits more efficiently such that more informed choices can be made.

Computer vision tools, when coupled with AI and drones or underwater cameras, can be harnessed for:

1) monitoring coral health *in situ* or *ex situ*,

2) identifying diseases/ mortality, and

3) tracking changes over time.

Environmental sensors and sensor networks are essential for monitoring water quality parameters like temperature, O_2, salinity, pH, and nutrient levels in coral tanks and on reefs. Data collected from these sensors, along with insights from AI, can be analyzed using interpretation and decision-support tools, enabling informed choices in coral reef management based on real-time environmental data. Additionally, the integration of remote sensing technologies with drones and underwater sensors offers the potential for remote coral nursery and restoration site monitoring, reducing the need for labor-intensive manual methods and providing valuable insights into coral health, growth, and environmental conditions.

Priority area 2b: Efficiency of asexual and sexual propagation

Techniques that employ high-volume/high mortality approaches analogous to those used for oyster aquaculture have been proposed to reduce expenses and labor and increase the scale at which corals can be cultured (Ridlon *et al.* 2023).

Larval-based restoration involves distributing vast quantities of coral larvae to damaged reefs to enhance settlement and recruitment, while ensuring high genetic diversity. Larval-based restoration leverages the natural reproductive capacity of corals, yielding millions of offspring, reducing early life stage mortality, and curbing loss due to larval drift.

Sexual reproduction has mostly been carried out in *ex situ* aquaculture facilities or laboratories. However, new techniques such as "coral rearing *in situ* basins," which are *in situ* floating containers hosting larvae on settlement tiles, are being explored to increase settlement efficiency without relying on land-based infrastructure (de la Cruz and Harrison 2017, Sellares-Blasco *et al.* 2021, Miller *et al.* 2022).

These techniques require collecting spawn during natural spawning events and rearing them in enclosures, thereby preventing dispersal by currents. Once ready to settle, the larvae are introduced to reefs through various methods, including containment under mesh or direct release as clouds; sometimes, robotic vehicles are used for precise deployment.

Corals that spawn synchronously can yield billions of eggs and sperm across a single hectare of reef (Álvarez-Noriega *et al.* 2016). Eggs are buoyant and concentrate in dense surface slicks under calm conditions, representing a rich, natural supply of sexual propagules for restoration purposes (Harrison *et al.* 2016).

Industrial-scale techniques for the collection of larval slicks on vessels are currently being explored, as this would allow for their relocation to habitats where coral stock is low and/or natural recruitment is compromised (Doropoulos *et al.* 2019, Harrison *et al.* 2021). This approach could offer a way to scale up restoration efforts and seed a wide variety of coral species.

A technological advancement in monitoring larvae-based projects has been developed by researchers from RRAP and the Queensland University of Technology, in which a robotic camera system utilizes AI to detect, count, and monitor the health and growth of individual coral larvae in *ex situ* facilities in real-time. The system's contact-free, modular design offers a low-cost, scalable solution for wider reef community restoration projects by providing a more effective method for tracking the growth of corals. At present, it is not yet known whether larval restoration ultimately delivers as many (or more) reproductively mature corals as more common coral fragment outplanting approaches.

Priority area 2c: Standardized software/hardware to optimize data collection and production efficiencies

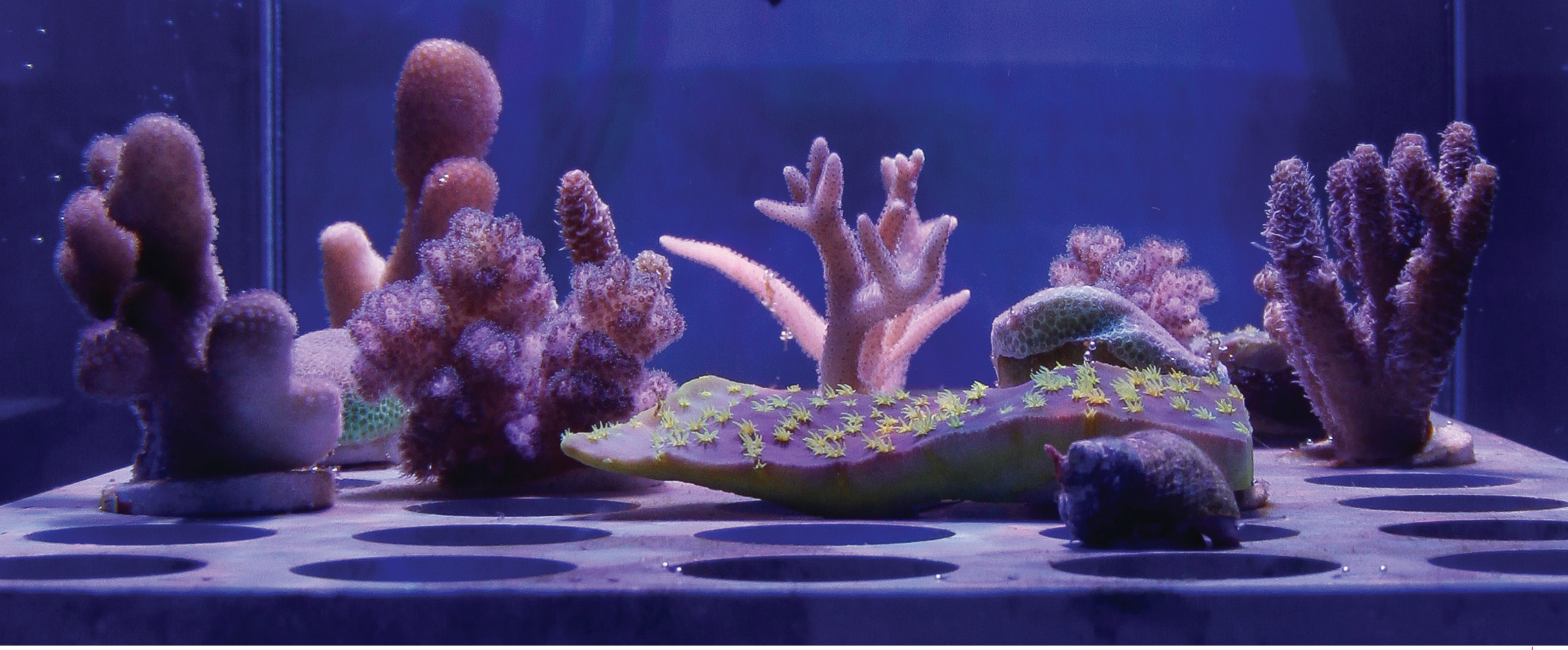
Schmidt-Roach *et al.* (2023) proposed the concept of adopting smart-farming technologies (e.g., Wang *et al.* 2021, Biazi *et al.* 2023) for coral farming. This approach transcends traditional precision farming, which focuses on catering to the unique requirements of specific species, by considering their native habitats.

Smart coral farming, in contrast, elevates this approach by incorporating a data-driven management strategy leveraging real-time data, enriched with contextual and situational awareness (Wolfert *et al.* 2017). This innovation allows for management actions to be dynamically tailored and triggered by immediate events, offering a more responsive and effective approach to coral farming. Smart coral farming is still in its nascent stages, but it promises significant enhancements in operational efficiency and cost-effectiveness.

Key to this transformation is the integration of "Information and Communication Technology" and "Internet of Things" solutions within aquaculture facilities. Advanced camera systems, for instance, can gather critical information through daily monitoring of animal behavior, providing invaluable insight (Macadam *et al.* 2021).

Automated image analysis deploying deep-learning has been shown to dramatically increase image analysis for coral reef monitoring (Gonzalez-Rivero *et al.* 2020), with Morand *et al.* (2022) exploring deep-learning approaches to assess coral performance on artificial structures *in situ*. Real-time computer vision systems developed for reef monitoring purposes, integrated with smart-farming technologies, could easily translate into guiding systems for high-throughput surface deployment of aquacultured corals.

The ability to monitor parameters in coral nurseries, land- or ocean-based, marks a significant leap forward in the precision and effectiveness of aquaculture practices.



Credit: Australian Institute of Marine Science | Phil Mercurio

While several products exist for real-time control of water quality in land-based nurseries originating from the aquarium industry (Jordaan and Umenne 2021), the marine research field (Low *et al.* 2020), and the fish aquaculture sector (e.g. Kamruzzaman *et al.* 2022), solutions for ocean-based nurseries usually lack real-time transmission of data. By combining data-driven management strategies with real-time data delivery, coral farming could be made more responsive and effective.

Priority area 2d: Simulations for improved decision-making

Lippmann *et al.* (2023) developed a model that facilitates strategic decision-making concerning the quantity, geographical positioning, and dimensions of coral nursery facilities. Additionally, their model addresses operational considerations, specifically the ideal duration of growth for cultivated coral within these facilities, with an overarching goal of cost minimization.

The study delves into how the length of time corals are grown in a facility influences their survival after being deployed, taking into account the necessary production volumes. A key takeaway from their findings is the critical role of accurate data in streamlining and enhancing the efficiency of coral aquaculture.

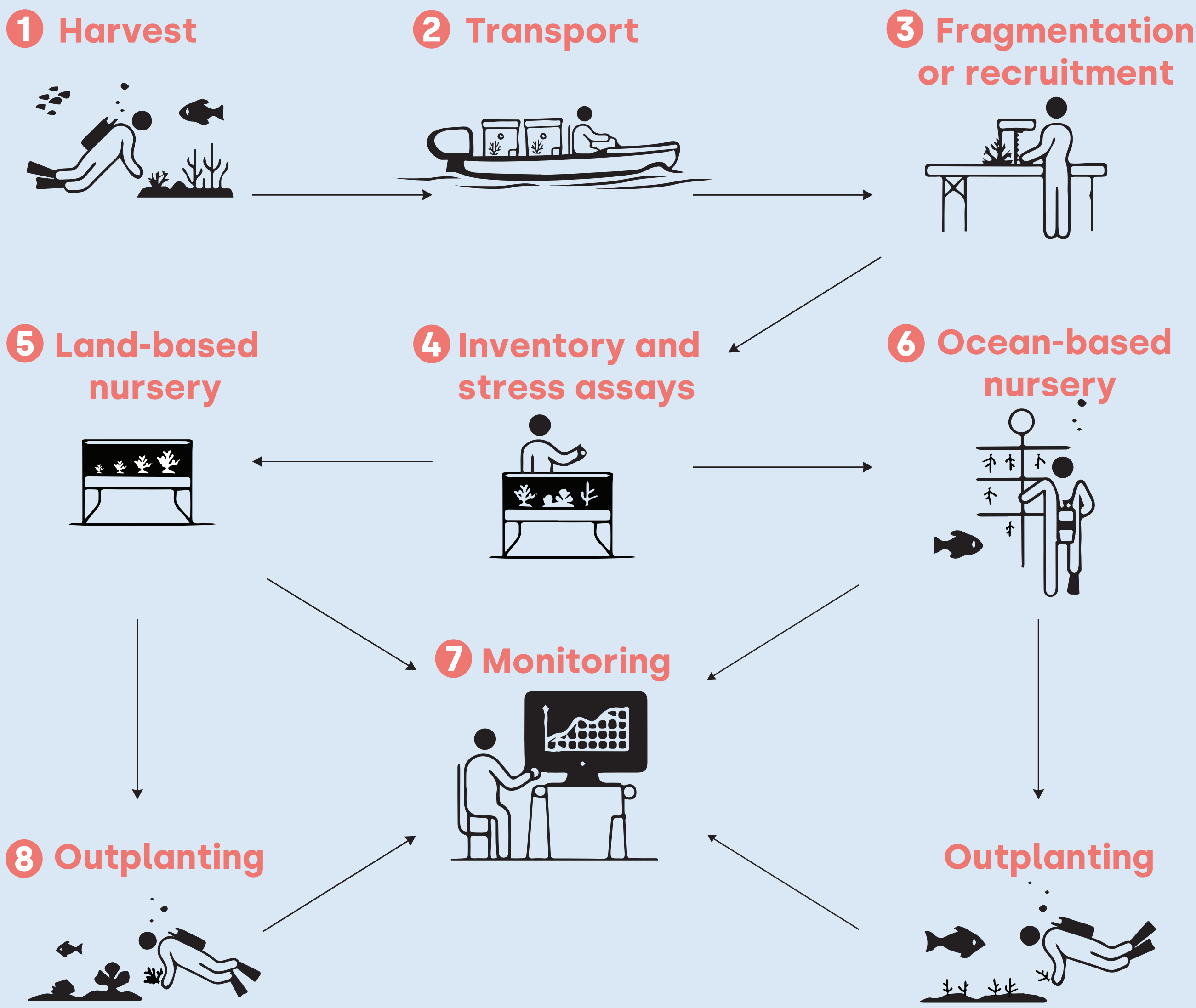
Despite these breakthroughs, holistic models for strategic decision-making in coral restoration that consider current or forecasted population status and demography per species are currently lacking. Approaches developed for adaptive fisheries management could be adopted for managing coral farming. For example, Punt (2017) emphasized the importance of quantifying trade-offs among different fisheries objectives, identifying and mathematically parameterizing these objectives and challenges to yield strategic advice. The approach could be useful for coral restoration as it would allow for a balanced consideration of ecological, economic, and social factors. In the context of coral aquaculture and restoration, the following criteria may be considered for a target coral species at local scales:

1. Expected long-term risk of the population depletion below thresholds required for reproductive activity
2. Significance of local loss of species for the ecosystem's functionality and ability to provide ecosystem services (economic value)
3. Economy (cost and time) of species propagation and intervention to rehabilitate
4. Intrinsic/cultural/social value of the population
5. Sustainability of intervention to rehabilitate (i.e., resilience)

By applying management strategy evaluation, coral restoration efforts can be optimized by considering the trade-offs between restoration goals and potential impacts; this could lead to more effective and sustainable restoration. However, decision-making in coral restoration may be hampered by the scarcity of detailed, precise, and current data.

Projects typically struggle with inadequate baseline data on coral health and distribution, which are crucial for evidence-based decisions. Consequently, this dearth of data can result in suboptimal, or even detrimental, restoration strategies. Addressing this challenge requires a concerted effort to amass datasets that comprehensively reflect the complexities of coral ecosystems and the nuances of restoration efforts.

Figure 1. Workflows of coral restoration.



General areas with R&D needs

1 Harvest
- Tools for fragment collection and transport
- Tools for gamete or larvae collection

2 Transport
- Transport containers and tools for wet or dry transport

3 Fragment/recruitment
- Adhesives
- Substrates
- Cutting tools

4 Inventory
- (Semi-) Automated systems for inventory management
- Software

Stress assays:
- Phenotyping
- Genetic assays

5 Land-based nursery
- LSS hardware and other facility components
- Modular infrastructure
- Control systems

6 Ocean-based nursery
- Modular/mobile infrastructure
- Sensor systems

7 Monitoring
- AI, sensor, and photogrammetric technologies
- Cloud storage and data processing

8 Outplanting
- Tools/techniques for rapid deployment
- Automated deployment

Table 5. Recommendations for technology advancements for coral production management and workflows.

Priority area	Topic	Technology	State of the art and current limitations	Features	Impact
2a	Automated inventory systems for livestock management	Tracking devices and AI	Tracking is time- and labor-intensive, tracking systems are in preparation	(Near) Real-time inventory of stocks	Allows for adaptive management, reduces costs, and promotes transparency. Future coral farming techniques will have to advance through an Industry 4.0 perspective, becoming more structured and intelligent. This means transitioning from reliance on experiential methods to approaches grounded in knowledge in order to enhance production efficiency.
	Automated stock monitoring	Computer vi-sion to monitor corals	Tools for precision aquaculture have been explored in related field such as fish aquaculture	Better control of stocks	Visual examination allows for the early detection of health issues and assists farmers in gauging and potentially managing growth rates, thereby helping to forecast the time until livestock is ready for harvesting.
2b	Efficiency of asexual and sexual propagation	Efficient coral spawning systems	(Shifted) spawning units are commercially available	Controlled light and temperature regimes	Improved coral reproduction and propagation
		Automated *ex situ* gamete collection and fertilization	Prototyping automated collection of gametes	Automated and controlled gamete collection	
		Industrial spawn slick harvesting	Proposed but not implemented	Relies on natural spawning	
		Larvae rearing at scale via AI	Proposed but not implemented		
		Settlement cues	Proposed but not implemented		

Credit: KAUST Coral Restoration Initiative

2.5 Integrating resilience

R&D efforts required to integrate resilience

Restoration projects often fail in the long-term due to the vulnerability of corals to heat waves (Foo and Asner 2020). With median costs per coral of approximately $10USD, each loss is associated with a significant cost, shaping the economy of coral restoration projects.

Adaptive management approaches and selection for resilience may assist to significantly increase survival (van Oppen *et al.* 2015, 2017, Humanes *et al.* 2021, Bay *et al.* 2023) and therefore lower the overall project cost (Schmidt-Roach *et al.* 2020). Investing in approaches that enhance the likelihood of coral outplant survival and reproductive performance may raise the cost per unit coral outplant but may reduce overall cost when assessments are based on long-term restoration success.

Integrating resilience through assisted adaptation is a critical component in the battle against coral reef degradation (Ridlon *et al.* 2023, Schmidt-Roach *et al.* 2023) and was the focus of the inaugural CORDAP workshop (Bay *et al.* 2023). It encompasses a range of innovative strategies aimed at enhancing coral resilience and adaptability by, amongst other means, transplanting stress-tolerant corals. Herein, we categorized these strategies and approaches into five priority areas, each of which plays a pivotal role in coral restoration by reinforcing the health and survival of restored reefs. Each of these approaches, from genetic resilience to environmental adaptability, also presents unique challenges and limitations, necessitating ongoing research and funding for effective and scalable coral restoration.

For coral restoration to effectively counteract the impacts of climate change, it is imperative to develop and implement resilience-oriented strategies that leverage assisted adaptation approaches (Figure 2). Such approaches must be scalable and high-throughput. The following areas were identified (Table 6):

1. Identification of resilient individuals
2. Selective breeding
3. Microbiome and symbiont manipulation
4. Stress-hardening
5. Co-culture and polyculture

Priority area 3a: Identification of resilient individuals

Assessing resilience in coral restoration, particularly thermal resilience, involves exploring both phenotypic and genotypic performance. Phenotypic variation, such as changes in host-symbiont associations, influences the coral response to thermal stress. For instance, high phenotypic variation in nursery-reared corals reflects variable responses to warming, indicating the significance of genetic variation in assessment of stress tolerance (Klepac *et al.* 2023).

Techniques like short-term acute heat stress assays (e.g., CBASS) may be effective in identifying resilient populations that will be crucial for conservation (Voolstra *et al.* 2021a-b). However, whether these methods are able to reliably identify resilient individuals within a population at scale, which is vital for restoration, has yet to be tested.

Recently, non-destructive, fluorescence-based methods/tools have emerged as low-cost strategies to track thermal stress biomarkers (Suggett *et al.* 2022, Hoadley *et al.* 2023). These techniques may assist in predicting coral bleaching susceptibility across different species, providing a scalable tool for coral restoration efforts. However, it remains to be determined if these symbiont-specific methods yield data that reflect the overall health of the holobiont.

Genotypically, resilient corals often maintain higher expression of thermal tolerance genes, like heat shock proteins, during environmental stress, highlighting the role of genetic factors in driving resilience (Barshis *et al.* 2013). Molecular methods may help in identifying diagnostic biomarkers for thermal stress (Mayfield 2022), further enhancing restoration strategies (Parkinson *et al.* 2018).

High-resolution genotyping arrays were created for *Acropora* corals and their dinoflagellate symbionts in the Caribbean (Kitchen *et al.* 2020). The approach includes a large number of single nucleotide polymorphism (SNP) probes, facilitating in-depth genetic analysis of these corals and their symbionts. However, these methods are not yet scalable across genera, are expensive, and require a high level of expertise. They need to be further developed to instead be cheaper, practitioner-friendly, and high-throughput are they to see more widespread adoption by coral restoration practitioners.

Advancing our capacity to reliably identify stress-resilient corals (*sensu* Mayfield *et al.* 2022a) promises to significantly increase the long-term success rates

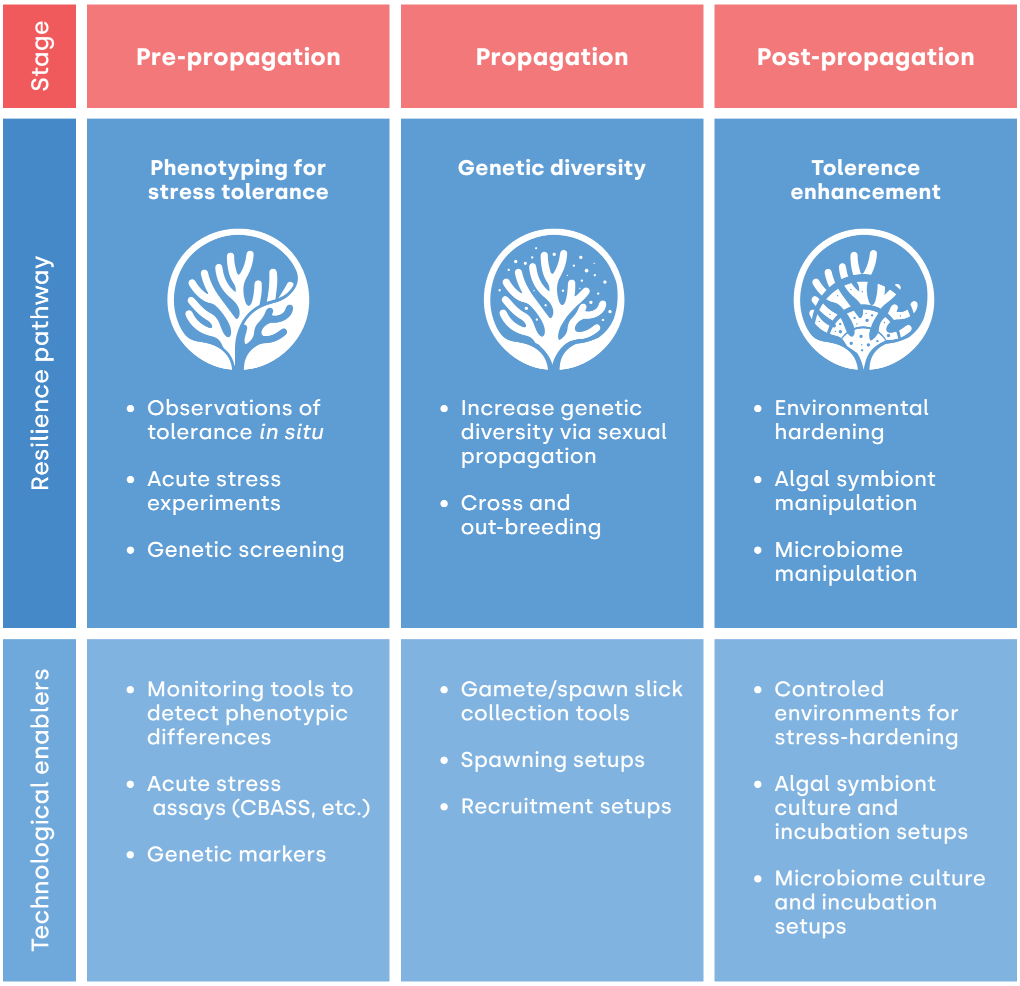


Figure 2. Pathways and technologies for promoting coral resilience.

of coral restoration initiatives. Yet, most pathways are currently still at experimental level and lack scalability and cost-efficiency. Tools for high-throughput phenotyping at an industrial scale, as available for agricultural science (Chawade *et al.* 2019, Smith *et al.* 2021), are absent for corals.

Further, tools need to be more accessible and user-friendly for practitioners in the field and affordable for applications in middle and low-income nations. Addressing these challenges is crucial for translating scientific advancements into practical, widespread coral restoration applications.

Priority area 3b: Selective breeding

Selective breeding, such as through interspecific and intraspecific hybridization, can accelerate adaptation by creating genotypes with enhanced climate resilience and improve environmental stress tolerance in corals, key factors for the success of coral reef restoration efforts (van Oppen *et al.* 2017, Howells *et al.* 2021).

Though selective breeding has the potential to support reef persistence in the face of climate change, challenges remain, particularly in the post-settlement and outplanting phases of restoration; these issues currently hamper its scalability (Humanes *et al.* 2021).

For most traits, heritability is generally high, and the thermal tolerance in offspring is often improved if at least one parent exhibits a higher level of thermal tolerance. However, heritability also differs across various life stages and among traits related to thermal tolerance (Bairos-Novak *et al.* 2021, Suggett and van Oppen 2022). Indeed, in some cases, hybrid larval performance does not align with previously observed thermal tolerance of adults in source populations (Zhang *et al.* 2022).

Therefore, while scaling up this approach has a high potential to ensure success in coral restoration, it is also important to pursue further knowledge development in understanding species and location-specific responses.

Further, maintaining a balance between selective breeding and natural sexual reproduction is essential to preserve the genetic integrity of outplanted offspring and minimize or manage potential trade-offs in fitness characteristics during the breeding process (Shaver *et al.* 2022).

Priority area 3c: Microbiome and symbiont manipulation

The co-culture of corals with beneficial organisms, including symbiotic dinoflagellates and other microbes, is being explored to enhance restoration success. This method taps into a rich body of knowledge on coral-microbial mutualisms to improve early survival in hatcheries and support later reef-building capacity (Suzuki *et al.* 2013, van Oppen *et al.* 2015, Chakravarti and van Oppen 2018, Buerger *et al.* 2020).

This concept leverages corals' ability to acquire diverse microbial symbionts. For example, bleached corals have been shown to acquire non-native Symbiodiniaceae, offering a novel method to form new symbiotic relationships between adult corals and heat-adapted dinoflagellate endosymbionts; this could consequently play a role in efforts to restore reefs with high climate resilience.

Probiotics have also been proven to mitigate coral bleaching and prevent mortality, with work now focused on identifying safe and effective microbial consortia for administration (Rosado *et al.* 2023).

Such studies suggest that culturing high temperature-tolerant symbionts and other beneficial microorganisms can provide a pathway for increasing climate resilience and enhancing the overall health and viability of coral populations by inoculating these symbionts in coral tissues and larvae (Doering *et al.* 2021). However, limitations and necessary improvements need to be considered in order to cultivate these beneficial microbes at a scale that would benefit coral restoration (Schultz *et al.* 2022).

Factors such as environmental conditions and species-specific symbiont preferences may disrupt long-term retention of these non-native and novel communities which in turn, may limit their utility in coral restoration efforts (Gabay *et al.* 2019, Camp *et al.* 2020, Claar *et al.* 2020).

The lack of large-scale means of identifying and culturing these microbes, as well as the absence of high-throughput delivery methods, also pose a significant issue.

Applications are currently limited to laboratory settings, where only a handful of coral colonies would benefit. To eventually apply these, strategies and techniques need to be developed to culture and deliver symbionts to corals at scale, which may be facilitated in land-based nurseries; the long-term retention of the benefits remains to be demonstrated.

Finally, off-target effects of mass dispensing of laboratory-cultured microbes into marine nurseries must also be properly assessed.

Credit: KAUST Coral Restoration Initiative

Priority area 3d: Stress-hardening

Coral conditioning, pre-conditioning, and/or environmental hardening represent a promising approach in coral restoration. This process involves exposing corals to controlled stressors to enhance their environmental stress tolerance.

Compared to other methods for boosting resilience highlighted herein, this approach is relatively well-explored (Bay *et al.* 2023). For instance, conditioning or epigenetic programming by exposure to increased temperature and pCO_2 in some coral species can improve their resilience to subsequent environmental change (van Oppen *et al.* 2017). More importantly, exposure of parental colonies to controlled stress regimes has been shown to lead to greater offspring settlement, survival, and growth, at least in some brooding coral species; these offspring would potentially demonstrate superior tolerance to climate change-associated stressors (Putnam *et al.* 2020). Whereas the underlying physiological mechanisms by which such stress-hardening occurs are not fully understood, large-scale application does not require such understanding as long as the benefits are consistent. Whereas scaling up these conditioning approaches is possible, maintaining conditioning infrastructure comes with high operating costs that might limit widespread adoption in developing countries.

Priority area 3e: Co-culture and polyculture

To improve the habitat and resilience of outplanted corals, co-culture and polyculture of reef-associated organisms like urchins, snails, and herbivorous fish may be beneficial.

Field experiments demonstrate that increasing the density of herbivorous Caribbean king crabs on coral reefs significantly reduces seaweed cover (Spardaro *et al.* 2021). This decline in seaweed fosters greater coral and fish abundance and diversity, offering a promising strategy for coral reef restoration in the Caribbean.

Polyculture involves growing a diverse range of species together, enhancing the overall health and resilience of the coral ecosystem, promoting growth, reducing disease spread, and creating a more natural and sustainable coral environment (Clements and Hay 2019). The productivity of stony corals is influenced by neighboring organisms, even without direct physical contact (Engelhardt *et al.* 2023). These findings highlight the importance of biodiversity in these systems and underscore the potential benefits of polyculture approaches in reef restoration.

Credit: The Ocean Agency

Table 6. Recommendations for technology advancements for boosting coral resilience.

Priority area	Topic	Technology	State-of-the-art and current limitations	Features	Impact
3a	Phenotyping/ genotyping	Acute stress tests	Not yet scalable	Cheap, user-friendly, high-throughput assay	Propagation of more stress-tolerant corals
	Phenotyping/ genotyping	Identifying biomarkers	Expensive and requires high level of expertise, not yet scalable	Cheap, user-friendly, high-throughput assay	
3b	Selective breeding	Intra- and interspecies hybridization	Requires a high level of expertise, traits may not be heritable, not yet scalable	Cheap, user-friendly, high-throughput protocols	
3c	Microbiome manipulation	Application of probiotics, manipulation of symbionts	High maintenance, may not have a lasting impact, not yet scalable	Minimized ecological risk and sustained genetic diversity	
3d	Environmental hardening	Conditioning and pre-conditioning	Exact mechanisms unknown, lack of parental conditioning research on broadcast spawners	Streamlined protocol requiring minimal training	
3e	Creating resilient habitat	Co-culture and polyculture	Common in land-based nurseries to co-culture corals alongside sea urchins and other herbivores, though not widely performed *in situ*	Cheap, low maintenance system featuring diverse array of invertebrates and other beneficial biota	A resilient habitat/ substrate in/on which corals can thrive with minimal maintenance

Credit: KAUST Coral Restoration Initiative

2.6 Efficient outplanting

The costs of labor, especially SCUBA diving, are a major part of the expenses in ocean-based nursery and coral outplanting projects.

Reducing the SCUBA time needed for each coral planted significantly lowers overall expenses, provided divers are limited by the number of tasks they can perform within the typical one-hour duration of a SCUBA dive in shallow, tropical coral reefs, as well as by the maximum number of dives they can safely do in a day.

Therefore, the main opportunities for improvement are centered around reducing or eliminating dive time, improving efficiency, and reducing risks of SCUBA accidents. This could be achieved by streamlining dive-related tasks, implementing nature-based solutions and adaptive management to increase efficiency, and potentially automating some of the tasks currently performed by humans (Table 7).

Priority area 4a: Attachment processes- reducing or eliminating manual diving efforts

Whereas loose corals have the ability to re-attach themselves to stable substrates, this may be hindered by even gentle movements. Consequently, most coral outplanting techniques aim to establish a firm connection with the new substrate through various methods, such as cementing, epoxy application, drilling and plugging, or using nails (Afiq-Rosli et al. 2017, Toh et al. 2017, Unsworth et al. 2019, Suggett et al. 2020, Humanes et al. 2021, Schmidt-Roach et al. 2023). Automated outplanting technologies offer a potential breakthrough if robotics could completely replace human-led dive operations for coral outplanting. Underwater drones, equipped with advanced navigation and imaging systems, could precisely position coral fragments on reefs. Innovative companies such as Reefgen (reefgen.io) and Seafoundry (www.seafoundry.com) are leading the way in these technological advancements, setting the stage for their broader application.

Nevertheless, moving from pilot experiments to a widespread adoption of these technologies will require a significant time and resource investment.

Priority area 4b: Strategies/techniques to increase survival of outplants

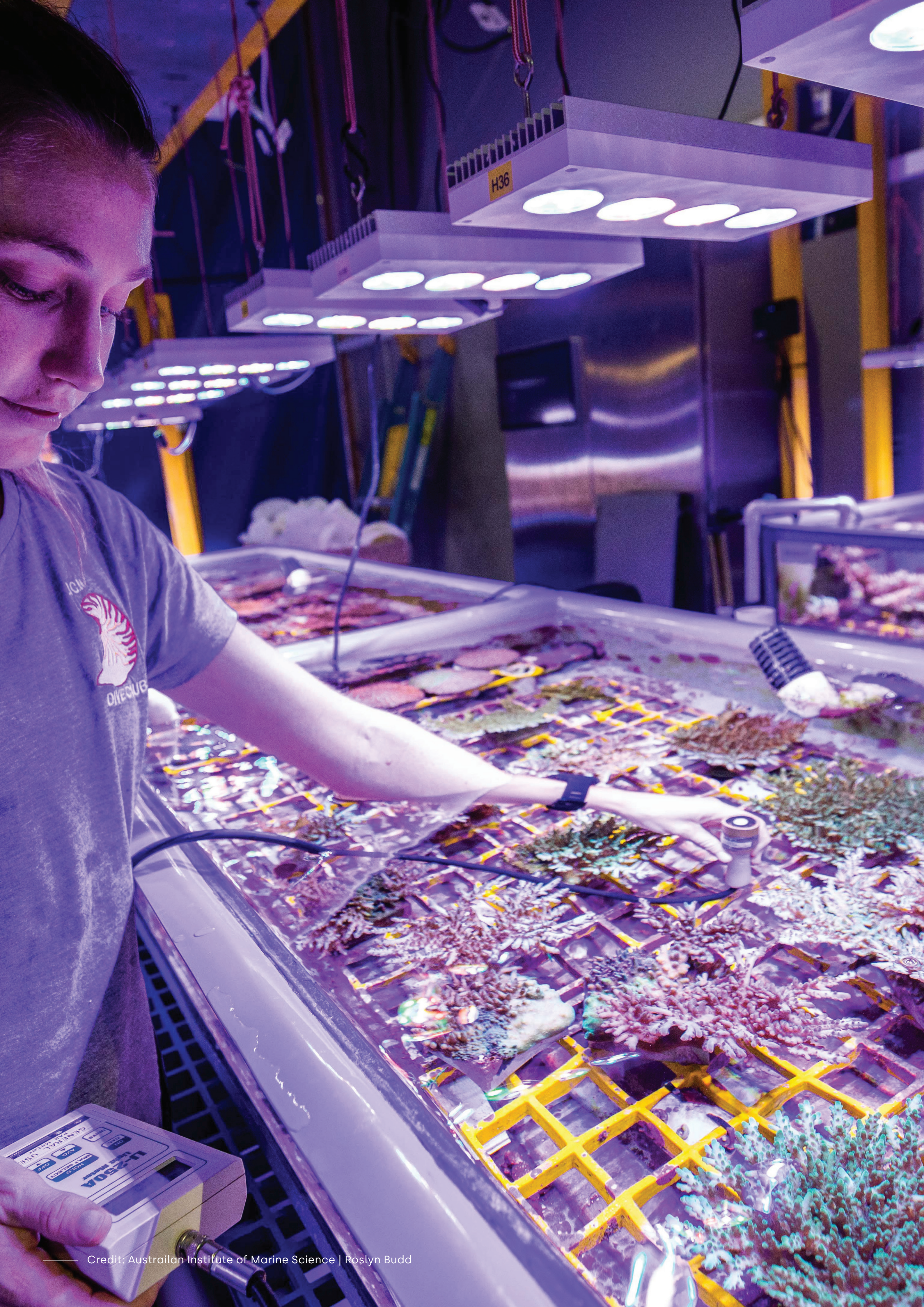
Increasing the survival of coral outplants is critical for the success of restoration projects, and approaches to do so include increasing resilience, priming outplant sites, improving attachment techniques, and/or employing software-assisted decision-making tools. Careful site selection is also a key factor. Remote sensing technologies are increasingly being used to identify optimal locations for coral transplantation by tracking parameters such as seawater quality and coral predator abundance (Foo and Asner 2019). For instance, Foo and Asner (2020) showed that outplant survival may largely depend on the temperature regime of the outplant site, and Jayanthi *et al.* (2021) conducted a multi-criteria, decision-support spatial analysis to evaluate the suitability of a coastal lagoon for aquaculture, an approach that could be transferred to identify suitable outplant sites.

Priority area 4c: Optimized design of coral-bearing devices that allow deployment without the intervention of divers and are effectively retained onto the seafloor

Chamberland *et al.* (2020) demonstrated that deploying structures seeded with coral larvae into the ocean in a less structured manner can greatly reduce underwater time. This method involves recruiting coral larvae to tripod structures that can be loosely placed on the seafloor. However, the use of sexually produced coral recruits resulted in low survival rates. Refinements in the designs of devices, enabling their placement on the seafloor without diver assistance and ensuring their stable retention underwater, are needed to further vet these technologies (Randall *et al.* 2021, 2023).

Table 7. Recommendations for outplanting.

Priority area	Topic	Technology	State of the art and current limitations	Features	Impact
4a	Attachment	Manual	Several techniques available	Solid attachment	Outplanting at scale
		Automatic	Proposed and at prototype stage	No divers involved	
		Seeded	Tested and at prototype stage		
4b	Site section and preparation	Priming of suitable sites	Implemented at small scale, further testing required	Nature-based approach	
		Predict suitable sites	Some models available	Remote sensing	



Credit: Austrailan Institute of Marine Science | Roslyn Budd

2.7 Monitoring

Current approaches for studying and monitoring the performance of coral reef restoration projects typically involve diver-held or stationary cameras, or the use of sensor buoys, with scientists predominantly depending on divers for monitoring surveys.

These techniques are often resource-intensive, both in terms of time and cost, primarily due to the extensive labor and costs required for diving operations and the manual processing/annotating of data. Additionally, these methods may not effectively capture the full spectrum of interactions among various reef organisms and their environments. There is a growing need for innovative tools that can enhance the scale and efficiency of coral reef monitoring over larger areas at a fraction of the currently needed times (Table 8).

Priority area 5a: Cost-effective, long-term monitoring approaches

A recent review suggests that coral reef research stands to benefit significantly from the burgeoning field of nanotechnology, opening the door to innovative tools tailored for coral monitoring (Roger *et al.* 2023). This includes the development of specialized diagnostic instruments, rapid tests, and advanced high-resolution monitoring of coral health.

In particular, the use of non-invasive nanoparticle-based sensors could be pivotal in detecting and tracking the onset and progression of physiological stress in coral environments, offering a new dimension in coral landscape assessment.

While satellite-based remote sensing systems are advancing, their ability to capture fine-scale spatial and temporal data, particularly in underwater environments, remains limited.

Nano-probes offer a promising solution for monitoring a range of abiotic and biotic factors such as oxygen (Koren *et al.* 2016), pH, heavy metals, eDNA, and mRNA. These nanoprobes can operate across various spatial scales, from individual coral colonies to broader reef habitats, and could be used *in situ* and *ex situ*. However, due to underwater communication challenges, use *in situ* would require periodic site visits for data collection or using devices that transmit very low-frequency radio waves. Testing these technologies in real-world scenarios is essential for advancing research and fostering multidisciplinary, problem-solving innovation in reef restoration.

Platz *et al.* (2020) explored the use of the autonomous benthic ecosystem and acidification measurement system to monitor coral restoration, focusing on changes in water chemistry. Their study, conducted in a Florida Keys coral nursery, revealed significant increases in the ratio of net community calcification to production after restoration.

This finding highlights the potential of metabolic monitoring as an effective remote tool for tracking the progress of coral restoration over time, offering valuable insights for resource management and restoration practices.

Priority area 5b: Cloud storage and advanced (automated) data processing

Over the last 10 years, there has been a surge in data related to coral reef restoration, encompassing the origins, genetic makeup, and performance of various coral strains.

Resource managers are tasked with overseeing a wide array of details, including permits, species, restoration sites, and performance metrics across different groups.

Simultaneously, researchers are producing extensive datasets that delve into the genetic, genomic, and phenotypic variations of corals.

Restoration experts, on the other hand, keep detailed records of coral fragment collection, genetic performance, outplanting sites, and survival rates. There are now efforts to collect and curate these data in open-source databases. The Coral Sample Registry (Moura *et al.* 2021), for example, assigns a unique accession number to each sample, which can be integrated into both existing and future data systems. The goal is to enable efficient tracking of coral samples across different platforms, unlocking more comprehensive insights into coral restoration.

With the advancement in technologies, and the ability to easily collect large amounts of data, data storage is becoming significantly more important.

Priority area 5c: Database design and curation and data analysis with AI.

Underwater digital photography is used in the vast majority of coral reef monitoring projects, yet significant time and expertise are required to extract meaningful ecological data from the images.

A promising solution to this bottleneck is the application of AI, such as deep learning, for automated image annotation (Gonzalez-Rivero *et al.* 2020). The CoralNet AI has seen widespread use in identifying corals and other reef inhabitants from underwater photos, while Cerulean AI, which is still in the testing phase, aims to simplify the creation, storage, and analysis of coral reef photomosaics. Furthermore, machine-learning algorithms can significantly improve coral reef mapping and feature detection from remote sensing data. This advancement has substantial implications for reef management (Hamylton *et al.* 2020).

These AI applications are versatile, capable of classifying coral genera or species, tracking growth, and assessing health, as shown in studies by Collin and Planes (2012), Mahmood *et al.* (2017), Lumini *et al.* (2020), Jamil *et al.* (2021), Mayfield *et al.* (2022b), and Fawad *et al.* (2023). They also facilitate the mapping and monitoring of entire habitats.

Table 8. Recommendations for monitoring.

Priority area	Topic	Technology	State of the art and current limitations	Features	Impact
5a	Long-term monitoring	Automated	Lack of scalability. Currently most projects feature manual monitoring by divers	Reduction of diver involvement	Coral detection and assessment
5b	Advanced data processing	Cloud storage and shared databases	First common databases available	Open-access storage	Data availability
5c	Artificial intelligence		Currently data processing is conducted manually, which is time sensitive and requires significant expertise	Straightforward to use, requiring minimal setup or specialised knowledge. Anyone can operate the technology efficiently without extensive training, making it widely accessible and convenient for a broad range of users	Data analysis


Credit: The Ocean Agency | Martin Colognoli

3. Coral reef restoration in low-income nations

This roadmap illustrates a way forward for technological advancements that can enhance scalability and efficiency of coral reef restoration efforts.

While technological advancements in coral reef restoration hold great promise, their benefits will only be fully realized if developing nations are actively included, supported, and benefit from them.

Developing countries are at the forefront of the coral reef crisis, experiencing the detrimental impacts of reef decline most acutely/intensely. It is crucial that they are included in the development and implementation of restoration technologies to ensure that they are realistic and adaptable to diverse socio-economic situations.

There is a risk that the high cost and complexity of new technologies could limit their accessibility in developing nations. For example, state-of-the-art technologies that automate tasks can significantly increase scale and reduce costs in developed nations. However, the expenses associated with these tools, their maintenance, and the specialized infrastructure and skills required to operate them may not be practical for developing nations, where most coral reefs are located.

While advanced tools that enhance efficiency and reduce effort are highly beneficial, they are ultimately useless if they are not accessible where they are needed most. Mechanisms must be in place to ensure that developing nations benefit from these advancements without the lag time (until adoption) that has historically been the case; in coral reef restoration, developing nations must be at the forefront of benefiting from these technologies, necessitating concerted efforts to ensure they are shared and accessible.

Beyond simply serving as beneficiaries, developing nations must be actively included in the development of these technologies to ensure that they are realistic and adaptable. Funding R&D projects from within these nations can lead to more innovative and contextually appropriate solutions.

Additionally, international collaborations and capacity development are essential to enable developing nations to access and utilize advanced restoration technologies. We need to invest in creating best practice guidelines, as well as training programs for local scientists, technicians, and community members to bridge the technological gap and ensure they can participate in large-scale restoration efforts.

Partnerships between universities, research institutions, and NGOs can facilitate the exchange of knowledge and skills.

Additionally, creating educational programs and workshops tailored to the specific needs of developing nations can empower local communities to take an active role in restoration projects. In the end, it is essential to prioritize technologies that are feasible and practical for a variety of socio-economic contexts. This will ensure that developing nations are not only participants in the development of, but also beneficiaries of advancements in, coral reef restoration.

Credit: The Ocean Agency

4. Building a blue economy for restoration

Governments have increasingly recognized their responsibility to address ecosystem degradation, leading to a surge in funding for restoration efforts that align with various national priorities.

By investing in these initiatives, governments aim not only to rehabilitate damaged environments but also create conditions conducive to economic growth and sustainability. This governmental support should translate into ecosystems that encourage private sector involvement, thereby promoting the blue economy.

Through strategic public funding and policy-making, governments can stimulate private investment in sustainable marine and coastal activities. This, in turn, can foster innovation and the development of new technologies aimed at preserving and enhancing marine ecosystems.

By creating a collaborative environment where both public and private sectors work towards common goals, the restoration and sustainable use of ocean resources can be significantly accelerated.

This integrated approach will help build resilient economies that benefit from healthy, thriving ecosystems while ensuring the long-term sustainability of marine resources.

5. Conclusions

The current landscape of coral reef restoration is marked by several challenges that impede its scale and effectiveness.

A key issue is the limited exchange of technical knowledge between practitioners and related industries. Although there are numerous ways to enhance aquaculture efficiency, either through existing methods or by adapting techniques from other fields, there is a gap in the strategic implementation and integration of these approaches. For instance, the coral aquaculture sector could benefit immensely from technologies used in fish aquaculture and the aquarium trade.

Another vital aspect is the utilization of reef restoration technologies that have achieved TRL9. These technologies are ready for large-scale application but are yet to be widely implemented. This lack of application and knowledge transfer can be attributed to several factors: a lack of coordinated efforts, limited funding, and the restricted scope of past and current restoration projects.

Typically, these projects operate in isolation, a trend that is poised for change with the advent of larger government-funded initiatives, such as those by the United States Defense Advanced Research Projects Agency.

To facilitate technology transfer and knowledge sharing, it is essential to establish cross-disciplinary working groups involving partners from organizations like CORDAP and including representatives from the aquarium trade, other aquaculture sectors, engineers, and coral restoration experts, as was the case for this workshop.

Standardization was highlighted as a key element for scalability across various categories; by establishing uniform and standardized practices and procedures, the adoption and implementation of effective technologies and methods in coral restoration can be significantly accelerated.

The strategies discussed highlight the importance of reducing labor and dive time in ocean-based coral nursery and outplanting projects to minimize costs and increase efficiency.

Innovative approaches such as automation and use of underwater drones, as explored by companies like Reefgen and Seafoundry, have the potential to revolutionize these operations by eliminating the need for divers.

Credit: The Ocean Agency | Martin Colognoli

Credit: KAUST Coral Restoration Initiative

6. Methods and analysis

This report aims to explore the technological advancements required for upscaling coral restoration efforts to create ecologically meaningful impacts.

To do so, the authors have grouped the innovation topics chosen by the workshop participants into five sections: industrial aquaculture, *in situ*/hybrid nursery systems, biological approaches, field-based monitoring, and measurements of success.

Each of these topic areas describes a general category associated with executing coral restoration at scale. Within each category, a number of more specific areas of potential innovation were rated based on four critical components:

- **Lead-time:** The length of time needed for R&D before innovations in the topic area can be effectively scaled.
- **Quality:** The potential impact that these innovations could have on enabling ecologically meaningful impact if successful.
- **Cost:** The amount of R&D funding needed in order to develop these innovations.
- **Flexibility:** The ability for these to be incorporated into reef restoration projects in different settings, with different ecological regimes and different resource capacities.

These four categories are not weighted to comment on relative importance but are described to offer a high-level analysis on the general state of innovation in each topic area, the impact potential that innovations could create for scaling reef restoration, and the resources needed to develop effective solutions (Supplementary tables 1, 2, and 3).

These ratings are meant to describe the potential of each topic to enable efficient and effective reef restoration at scale. The numbers are based on data derived from expert opinions as shared during the January 2023 CORDAP workshop, and therefore all figures are high-level estimates.

7. Appendix

Supplementary table 1: Scoring scheme. Price estimates are in United States dollars. TRL = technology readiness level.

Category	**Lead-time**		**Quality**			**Cost**		**Flexibility**	
Score	Readiness	Time to TRL9	Critical need	Benefits	Risk	Investment to TRL9	Cost efficiency	Scalability	Global feasibility
1	TRL 1-9	12+ years	Useful	Few	Catastrophic	$50M and above	Super expensive	Site specific/ several meters	Local
2	TRL 1-9	9 - 12 years	Makes a difference	Some	Serious	$10M - $50M	Expensive	Little/ hectare	Nation-dependant
3	TRL 1-9	6 - 9 years	Important	Meaningful	Moderate	$2M - $10M	Reasonable	Fairly/ square km	Nation-dependant
4	TRL 1-9	3 - 5 years	Very important	Significant	Low	$500K - $2M	Affordable	Widely/100s of kms	Most places
5	TRL 1-9	1 - 3 years	Essential	Huge	Not serious	Under $500K	Very affordable		Everywhere
Weight	*(x/2)/5*	*x/1*	*x/1*	*x/5*	*x/5*	*x/1*	*x/2*	*x/2.5*	*x/1*
Category score	*Sum/5.9*		*Sum/7*			*Sum/7.5*		*Sum/7*	

Supplementary table 2a: Scoring results for technologies.

Category	Subject	Feasibility	Cost Efficiency	Readiness	Time to TRL9	Average of investment to TRL9	Risk	Benefit	Critical need	Scalability
Artificial reef-related	Artificial reef design	3	3	4	4.5	2.5	3	2.5	2.5	2
	Artificial reef materials	5	5	4	5	3	3	5	5	5
Assisted evolution-related	Assays/mapping to identify resilient genotypes	5	5	7	5	3	5	5	5	5
	Genetic lab integration/selection	1	2	7	5	4	5	3	1	2
	Microbiome manipulation	3	3.5	2.5	2	3	2.5	4	2	1.5
	Phenotyping	4	4	7	5	4	5	5	4	4
	Selective breeding/outplaning	4.5	4.5	4	4	3.5	3.5	4.5	4.5	4
	Symbiont manipulation/heat application	3	2	4	4	3	3	4	4	3
Attachment mechanisms	Adhesives	5	5	4	5	5	4.7	4	4	5
	Aesthetic design	2.5	3.5	7.5	5	4.5	4	4	3	2.5
	In situ treatments	5	5	1	2	2	3	5	5	5
	Mechanical attachment	5	5	8	5	5	5	4	4	5
	Natural based/alternative antifouling	3	3	4	4	4	3	4	5	3
	Standardized attachment	3	4	5	5	5	5	5	4.5	4
Automation for sexual reproduction	Automated larval collection	3	5	6	5	4	5	4	4	5
	Automated larval dispersal	3	5	5	4	4	5	4	4	5
	Automated larval holding	3	5	8	5	5	4	4	4	5
Cleaning-related	Antifouling treatment	4.7	4.3	3.3	3.8	3	3.7	4.3	4.7	5
	Chemical (tanks)	3	4	5	5	5	4.5	3.5	5	5
	Lasers	2	4	3	5	4	3	5	5	5
	Mechanical (brushes, siphoning etc.)	2	3.7	1.3	4.3	4.3	3.7	3	4.7	5
	Water jets	2	3	5	4	4	2	2	3	5
Deployment systems	Autonomous outplanting	3	5	2	2	2	4	5	5	5
	Outplanting devices	3.5	4	4	4.5	3.5	3.5	3.5	4.5	4.5
	Semi-automated outplanting	4	4	4.5	4	3.5	4.5	4	4	4.5
Enhancement infrastructure	Growth	3.5	3.5	2	3.5	2.5	3.5	5	4.5	4.5
	Managing infection risks through manipulating microbiome	1	2	3	3	2	3	3.5	2	1
	Probiotic cultures	2	2	6	4	3	5	5	5	3
	Stress treatments/hardening	2.5	2.5	4.5	3.5	2.5	4	4	3	2.5
Facility-related	Control and information integration among systems	3.5	4	6.5	5	4.5	4.5	5	3.5	4
	Energy efficiency	5	4.5	8	5	3.5	4.5	5	5	5
	Enterprise management system	5	4	6	5	5	5	5	5	5
	Standardization (tools, light, etc.)	3	3.2	5	4.4	3.2	5	4.6	4.8	4.4
Facility type	Hybrid facilities *ex/in situ* nurseries	3	4	6	5	4	4	4	5	3
	Modular - mobile facilites	4.7	4	7	4.7	3.3	4.7	4.7	4.3	4.7
Field-based	Bioacoustic approaches for attracting herbivores or coral larvae	4	4	7	5	4	3	3	2	3
	Chemical cues for settlement of organ-isms (inc. biofilms etc.)	3	2	3	4	2	3	4	2	2
	Data-informed site selection	4	3	1	3	2	4	5	5	4
	Seeding	3	5	1	3	3	4	4	5	3
	Targeted antifouling chemicals	3.5	3.5	4	4.5	4	4	5	3.5	3
Field-monitoring-related	3D mapping	4.8	4.8	6.2	4.8	3.8	4.8	4.6	4.4	5
	Autonomous monitoring/mapping	3.3	4.3	5	4.7	4	4.3	4.3	4	4.3
	Field sensors	4.7	4	4.3	3.3	2.7	5	4	4	5
Fish ecology-related	Chemical ecology fish/grazers	3	2	1	3	3	3	5	5	2
	Co/polyculture	4	3	6	5	3	4	5	5	2
	Co/polyculture of grazing organisims for *in/ex situ* facilitation	3	3	6	5	4	4	5	5	3
	Fish ecology to optimize nursery usage/ structure designs	5	5	5	5	4	5	5	2	2
Husbandry-realted	Best practice guidelines	5	5	6.5	4.5	5	5	5	5	5
	Broodstock collection	1.5	3	7	5	4.5	5	4.5	3.5	3
	Co-culture of beneficial biota	4.3	4	6.7	4.7	4	5	5	4.7	4.7
	Co/polyculture	3	3	6	5	4	4	5	5	3
	Coral disease identification/prevention	3	2.7	5.7	3.7	3.3	4	4.7	4.7	3.3
	Feed production/delivery	3.7	3.7	5	5	5	4.3	4.7	4.7	4.3

Supplementary table 2b: Scoring results for technologies (cont').

Category	Subject	Feasibility	Cost Efficiency	Readiness	Time to TRL9	Average of investment to TRL9	Risk	Benefit	Critical need	Scalability
Husbandry-related (continued)	Feeding (optimizing diets)-type, timing. and placement in tank	4.5	4.5	7	4.5	4.5	5	5	4.5	4.5
	Moving corals/co-cultured organisms	3.3	2.3	3	5	4	4.7	1.7	2.7	5
	Rapid proxies/tests to assess coral health and identify pathogens	3.5	2.5	4.5	4.5	4	5	4.5	5	4.5
In situ nursery options	Auto ballasting (for shading, storms etc.)	3	3	7	5	5	5	4	4	3
	Collecting spawn in the nursery, channel-ling the slick to the *in situ* nursery	3	3	6	5	5	5	5	3	3
	Nursery that becomes a reef	4	4	7	5	5	3	3	4	2
	Pre-probiotic delivery systems	2	2	7	4	3	2	3	1	2
	Purposed-built vessels, offshore nurseries	2	1	5	4	3	5	4	3	3
	Semi-submersible coral platform that can be towed, large-scale, long distance	2	3	8	5	5	5	3	3	2
	Surface accessibly operated nurseries (limited diving required)	4	3	5	5	5	5	5	4	4
LSS-related	Equipment monitoring	2	3	5	5	3	5	4	3	3
	Lighting lenses/refractors	2	4.5	4	4.5	3.5	5	4.5	5	4
	Water chemistry (management, manipulation)	2.5	2.5	4	4.5	3	4	4	3	2.5
Materials/ tools-related	Automated micro-fragmentation (of coral colonies)	3	3.3	1.7	4	2.3	4.7	4.7	4	5
	Automated workflows	5	5	8	5	5	5	5	5	5
	Compatible attachment systems	4	3.3	5	5	5	5	5	5	5
	Crates/tracks	3	4	7	5	5	5	4	5	4
	Fragmentation efficiency tools	4.7	3	2.7	4.7	4	5	5	4.3	5
	Roof and shaders for natural light (dy-namic spectral manipulation)	2.5	3	4	3.5	3.5	5	4.5	3.5	4
	Sheeting tissue propagation	3.5	4.3	5	4.8	3.8	4.8	4.3	3.3	3.8
	Substrates for growth	4	4	5	4	2.5	4.5	4.5	5	5
	Tiles and settlement devices	4.5	4	5.5	5	3.5	5	5	5	5
	Transport containers	3	3	5	5	4	5	5	4	3
Monitoring-related	Inventory management	4	3	6	5	4	5	5	5	5
	AI/machine-learning	3.5	3	6	5	3.5	3	5	4.5	5
	Buoyant weight gauge for growth/force	2	3	5	5	5	4	3	3	4
	Cameras	3.5	3.5	6.5	5	4	3	5	5	5
	Data processing and actuation	4	3	3.5	5	4	3	5	4.5	4.5
	eDNA	4	2.5	7	4.5	3.5	3.5	3	3	3.5
	Health/early-warning systems	5	2	4	5	3	2	4	5	5
	Inventory tracking	3.7	3	6	5	4	3.7	4.3	4.7	4.3
	Radio frequency identification (RFID)	2	4	7	5	4	5	3	3	3
	Standardized imaging vertical vs. table nurseries	3	3	6	5	4	5	4	4	3
	Water chemistry	3	2	5	5	3	5	5	5	5
Others	Climate control (environmental param-eters)	3	3	7	5	3	5	5	5	4
	Industrial-scale symbiont culture	3	3	7	5	4	3	4	4	4
	Labor	4.7	4.3	6	5	5	5	4.7	5	5
	Minimize time to reproductive size	5	4	1	4	3	2	5	5	5
	Pre-conditioning of the substrate before outplanting (cleaning)	5	4	5	5	4	3	5	4	2
	Production-output for outplanting	5	5	7	5	5	5	5	5	5
	Targeted antifouling chemicals	4	3	4	4	5	3	5	5	2
Surface deployment systems/ seeding devices		3	5	2	5	3	5	5	5	5

Supplementary table 2c: Scoring results for technologies (cont').

Category	Subject	Feasibility	Cost Efficiency	Ready	Time to TRL9	Average of investment to TRL9	Risk	Benefit	Critical need	Scalability
Tank-related	Coral disease identification/prevention	5	4	9	9	5	5	2	1	3
	Early life stage tanks	3	4	7	5	4	5	4	4	3
	Flow regimes	5	5	9	5	5	5	5	5	5
	Incubation tanks (symbionts, probiotics)	3	3	5	5	4	3	4	2	3
	Multiple layers to maximize space (vertical farming	3	3	2.5	3.5	2.5	4	4.5	4.5	4
	Phase-shift spawning	5	5	9	5	5	5	5	5	5
	Settlement/recruitment tanks	3	4	7	5	4	5	4	4	3
	Spawning tanks	3	4	7	5	4	5	4	4	3
Tracking-related	Apps for workflow facilitation	5	4.5	6.5	5	4.5	5	5	5	5
	eDNA dip-stick monitoring for pathogens	5	5	7	5	2	5	5	4	5
	eDNA monitoring	2	2	6	3	3	5	5	2	2
	Effective inventory management	4	4.5	6	5	4.5	5	5	4.5	4.5
	Phenotyping	3.5	3	4.5	4.5	4	5	5	5	4
Transport and logistics	Adjustable buoyancy and towable nursery	5	5	1	5	5	5	3	3	5
	Standardized transport	5	5	2	5	5	5	5	5	5

Supplementary table 3a: Scoring results for technologies scrutinized and scored based on four key elements: 1. Lead-time, 2. Quality, 3. Cost, and 4. Flexibility.

Category	Subject	Lead-time	Quality	Cost	Flexibility	Total
Artificial reef and structure	Artificial reef design	0.83	0.51	0.53	0.54	0.61
	Artificial reef materials	0.92	0.94	0.73	1	0.9
Assisted evolution-related	Assays/mapping to identify resilient genotypes	0.97	1	0.73	1	0.92
	Genetic lab integration/selection	0.97	0.37	0.67	0.26	0.57
	Microbiome manipulation	0.38	0.47	0.63	0.51	0.5
	Phenotyping	0.97	0.86	0.8	0.8	0.86
	Selective breeding/outplanting	0.75	0.87	0.77	0.87	0.81
	Symbiont manipulation/heat adaptation	0.75	0.77	0.53	0.6	0.66
Attachment mechanisms	Adhesives	0.92	0.82	1	1	0.93
	Aesthetic design	0.97	0.66	0.83	0.5	0.74
	In situ treatments	0.36	0.94	0.6	1	0.72
	Mechanical attachment	0.98	0.83	1	1	0.95
	Nature-based/alternative antifouling	0.75	0.91	0.73	0.6	0.75
	Standardized attachment	0.93	0.93	0.93	0.66	0.86
Automation for sexual repro-duction	Automated larval collection	0.95	0.83	0.87	0.71	0.84
	Automated larval dispersal	0.76	0.83	0.87	0.71	0.79
	Automated larval holding	0.98	0.8	1	0.71	0.87
Cleaning-related	Antifouling treatment	0.71	0.9	0.69	0.95	0.81
	Chemical (tanks)	0.93	0.94	0.93	0.71	0.88
	Lasers	0.9	0.94	0.8	0.57	0.8
	Mechanical (brushes, siphoning, etc.)	0.76	0.86	0.82	0.57	0.75
	Water jets	0.76	0.54	0.74	0.57	0.65
Deployment systems	Autonomous outplanting	0.37	0.97	0.6	0.71	0.66
	Outplanting devices	0.83	0.84	0.73	0.76	0.79
	Semi-automated outplanting	0.75	0.81	0.73	0.83	0.78
Enhancement infrastructure	Growth	0.63	0.89	0.57	0.76	0.71
	Managing infection risks through manipulating microbiome	0.56	0.47	0.4	0.2	0.41
	Probiotic cultures	0.78	1	0.53	0.46	0.69
	Stress treatments/hardening	0.67	0.66	0.5	0.5	0.58
Facility-related	Control and information integration among systems	0.96	0.77	0.87	0.73	0.83
	Energy efficiency	0.98	0.99	0.77	1	0.93
	Enterprise management system	0.95	1	0.93	1	0.97
	Standardization (tools, light, etc.)	0.83	0.96	0.64	0.68	0.78
Facility type	Hybrid facilities: *ex situ* and *in situ* nurseries	0.95	0.94	0.8	0.6	0.82
	Modular - mobile facilities	0.91	0.89	0.71	0.93	0.86
Field-based	Bioacoustics for attraction of herbivores and coral larvae	0.97	0.46	0.8	0.74	0.74
	Chemical cues for settlement of organisms (incl. biofilms)	0.73	0.49	0.4	0.54	0.54
	Data-informed site selection	0.53	0.97	0.47	0.8	0.69
	Seeding	0.53	0.94	0.73	0.6	0.7
	Targeting antifouling chemicals	0.83	0.76	0.77	0.67	0.76
Field monitoring-related	3D mapping	0.92	0.9	0.83	0.97	0.9
	Autonomous monitoring/mapping	0.88	0.82	0.82	0.72	0.81
	Field sensors	0.64	0.83	0.62	0.95	0.76
Fish ecology-related	Chemical ecology fish/grazers	0.53	0.94	0.53	0.54	0.64
	Co/polyculture	0.95	0.97	0.6	0.69	0.8
	Co/polyculture of grazing organisms for *in/ex situ* facilitation	0.95	0.97	0.73	0.6	0.81
	Fish ecology to optimize nursery usage/structure designs	0.93	0.57	0.87	0.83	0.8
Husbandry-related	Best practice guidelines	0.87	1	1	1	0.97
	Broodstock collection	0.97	0.77	0.8	0.39	0.73
	Co-culture of beneficial biota	0.9	0.95	0.8	0.89	0.89
	Co/polyculture	0.95	0.97	0.73	0.6	0.81
	Coral disease identification/prevention	0.72	0.91	0.62	0.62	0.72
	Feed production/delivery	0.93	0.92	0.91	0.77	0.88
Category	Subject	Lead-time	Quality	Cost	Flexibility	Total

Husbandry-related (continued)	Feeding (optimizing diets)-type, timing and placement in tank - assessed developing in a range of diets	0.88	0.93	0.9	0.9	0.9
	Moving corals/co-cultured organisms	0.9	0.56	0.69	0.76	0.73
	Rapid proxies/test to assess coral health and identify pathogens	0.84	0.99	0.7	0.76	0.82
In situ nursery operations	Auto-ballasting (for shading, storms, etc.)	0.97	0.83	0.87	0.6	0.82
	Colleting spawn in the nursery, channelling the slick to *in situ* nursery	0.95	0.71	0.87	0.6	0.78
	Nursery that becomes a reef	0.97	0.74	0.93	0.69	0.83
	Pre-probiotic delivery systems	0.8	0.29	0.53	0.4	0.5
	Purposed-built vessels, off-shore nurseries	0.76	0.69	0.47	0.46	0.59
	Semi-submersible coral platform that can be towed at large-scale over long distances	0.98	0.66	0.87	0.4	0.73
	Surface accessible operated nurseries (limited diving required)	0.93	0.86	0.87	0.8	0.86
LSS-related	Equipment monitoring	0.93	0.69	0.6	0.46	0.67
	Lighting lenses/refractors	0.83	0.99	0.77	0.51	0.77
	Water chemistry (management, manipulation)	0.83	0.66	0.57	0.5	0.64
Materials/tools-related	Automated micro-fragmentation (of coral colonies)	0.71	0.84	0.53	0.71	0.7
	Automated workflows	0.98	1	1	1	1
	Compatible attachment systems	0.93	1	0.88	0.86	0.92
	Crates/racks	0.97	0.97	0.93	0.66	0.88
	Fragmentation efficiency tools	0.84	0.9	0.73	0.95	0.86
	Roof and shaders for natural light (dynamic spectral manipulation)	0.66	0.77	0.67	0.59	0.67
	Sheeting tissue propagation	0.89	0.72	0.78	0.71	0.78
	Substrates for growth	0.76	0.97	0.6	0.86	0.8
	Tiles and settlement devices	0.94	1	0.73	0.93	0.9
	Transport containers	0.93	0.86	0.73	0.6	0.78
Monitoring-related	Inventory management	0.95	1	0.73	0.86	0.88
	AI/machine-learning	0.95	0.87	0.67	0.79	0.82
	Buoyant weight gauge for growth/force	0.93	0.63	0.87	0.51	0.74
	Cameras	0.96	0.94	0.77	0.79	0.86
	Data processing and actuation	0.91	0.87	0.73	0.83	0.84
	eDNA	0.88	0.61	0.63	0.77	0.73
	Health/early-warning systems	0.92	0.89	0.53	1	0.83
	Inventory tracking	0.95	0.9	0.73	0.77	0.84
	Radio frequency identification (RFID)	0.97	0.66	0.8	0.46	0.72
	Standardized imaging: vertical vs. table nurseries	0.95	0.83	0.73	0.6	0.78
	Water chemistry	0.93	1	0.53	0.71	0.79
Others	Climate control (environmental parameters)	0.97	1	0.6	0.66	0.81
	Industrial-scale symbiont culture	0.97	0.77	0.73	0.66	0.78
	Labor	0.95	0.99	0.96	0.95	0.96
	Minimize time to reproductive size	0.69	0.91	0.67	1	0.82
	Pre-conditioning of the substrate before outplanting (cleaning)	0.93	0.8	0.8	0.83	0.84
	Production output for outplanting	0.97	1	1	1	0.99
	Targeted antifouling chemicals	0.75	0.94	0.87	0.69	0.81
Surface deployment systems/ seeding		0.88	1	0.73	0.71	0.83
Tank-related	Coral disease identification/prevention	1.68	0.34	0.93	0.89	0.96
	Early life stage tanks	0.97	0.83	0.8	0.6	0.8
	Flow regimes	1	1	1	1	1
	Incubation tanks (symbionts, probiotics)	0.93	0.49	0.73	0.6	0.69
	Multiple layers to maximize space (vertical farming)	0.64	0.89	0.53	0.66	0.68
	Phase-shift spawning	1	1	1	1	1
	Settlement recruitment tanks	0.97	0.83	0.8	0.6	0.8
	Spawning tanks	0.97	0.83	0.8	0.6	0.8
Tracking-related	Apps for workflow facilitation	0.96	1	0.9	1	0.96
	eDNA dip-stick monitoring for pathogens	0.97	0.86	0.6	1	0.86
	eDNA monitoring	0.61	0.57	0.53	0.4	0.53
	Effective inventory management	0.95	0.93	0.9	0.83	0.9
	Phenotyping	0.84	1	0.73	0.73	0.83
Transport and logistics	Adjustable buoyancy and towable nursery	0.86	0.66	1	1	0.88

8. References

Afiq-Rosli L, Taira D, Loke HX, Toh TC, Toh KB, Ng CSL, *et al.* (2017) *In situ* nurseries enhance coral transplant growth in sedimented waters. *Marine Biology Research* 13(8): 878-887.

Albalawi HI, Khan ZN, Valle-Pérez AU, Kahin KM, Hountondji M, Alwazani H, *et al.* (2021) Sustainable and eco-friendly coral restoration through 3D printing and fabrication. *ACS Sustainable Chemistry & Engineering* 9(37): 12634-12645.

Amar KO, Rinkevich B (2007) A floating mid-water coral nursery as larval dispersion hub: testing an idea. *Marine Biology* 151: 713-718.

Anthony K, Bay LK, Costanza R, Firn J, Gunn J, Harrison P, *et al.* (2017) New interventions are needed to save coral reefs. *Nature Ecology & Evolution* 1(10): 1420-1422.

Antonucci F, Costa C (2020) Precision aquaculture: a short review on engineering innovations. *Aquaculture International* 28(1): 41-57.

Bairos-Novak KR, Hoogenboom MO, van Oppen MJH, Connolly SR (2021) Coral adaptation to climate change: meta-analysis reveals high heritability across multiple traits. *Global Change Biology* 27(22): 5694-5710.

Baria MVB, Villanueva RD, Guest JR (2012) Spawning of three-year-old *Acropora millepora* corals reared from larvae in northwestern Philippines. *Bulletin of Marine Science* 88(1): 61-62.

Barshis DJ, Ladner JT, Oliver TA, Seneca FO, Traylor-Knowles N, Palumbi SR (2013) Genomic basis for coral resilience to climate change. *Proceedings of the National Academy of Sciences of the United States of America* 110(4): 1387-1392.

Barton JA, Willis BL, Hutson KS (2017) Coral propagation: a review of techniques for ornamental trade and reef restoration. *Reviews in Aquaculture* 9(3): 238-256.

Bay LK, Ortiz JC, Humanes A, Riginos C, Baums IB, Aranda, M, *et al.* (2023) CORDAP R&D Technology Roadmap for Understanding the Natural Adaptation and Assisted Evolution of Corals to Climate Change.

Bay LK, Rocker M, Boström-Einarsson L, Babcock R, Buerger P, Cleves P, *et al.* (2019) Reef Restoration and Adaptation Program: Intervention Technical Summary. A report provided to the Australian Government by the Reef Restoration and Adaptation Program (89 pp).

Bayraktarov E, Stewart-Sinclair PJ, Brisbane S, Boström-Einarsson L, Saunders MI, Lovelock CE, *et al.* (2019) Motivations, success, and cost of coral reef restoration. *Restoration Ecology* 27(5): 981-991.

Baums IB, Baker AC, Davies SW, Grottoli AG, Kenkel CD, Kitchen SA, *et al.* (2019) Considerations for maximizing the adaptive potential of restored coral populations in the western Atlantic. *Ecological Applications* 29(8): e01978.

Berman O, Levy N, Parnas H, Levy O, Tarazi E (2023) Exploring new frontiers in coral nurseries: leveraging 3D printing technology to benefit coral growth and survival. *Journal of Marine Science and Engineering* 11(9): 1695.

Biazi V, Marques C (2023) Industry 4.0-based smart systems in aquaculture: a comprehensive review. *Aquacultural Engineering* 103: 102360.

Blanco-Pimentel M, Evensen NR, Cortés-Useche C, Calle-Triviño J, Barshis DJ, Galván V, *et al.* (2022) All-inclusive coral reef restoration: how the tourism sector can boost restoration efforts in the Caribbean. *Frontiers in Marine Science* 9: 931302.

Boström-Einarsson L, Babcock RC, Bayraktarov E, Ceccarelli D, Cook N, Ferse SCA, *et al.* (2020) Coral restoration- a systematic review of current methods, successes, failures and future directions. *PLoS ONE* e0226631.

Bove CB, Mudge L, Bruno JF (2022) A century of warming on Caribbean reefs. *PLoS Climate* e0000002.

Buerger P, Alvarez-Roa C, Coppin CW, Pearce SL, Chakravarti LJ, Oakeshott JG, *et al.* (2020) Heat-evolved microalgal symbionts increase coral bleaching tolerance. *Science Advances* 6(20): eaba2498.

Camp EF, Suggett DJ, Pogoreutz C, Nitschke MR, Houlbreque F, Hume BC, *et al.* (2020) Corals exhibit distinct patterns of microbial reorganisation to thrive in an extreme inshore environment. *Coral Reefs* 39(3): 701-716.

Chakravarti LJ, van Oppen MJ (2018) Experimental evolution in coral photosymbionts as a tool to increase thermal tolerance. *Frontiers in Marine Science* 5: 227.

Chawade A, van Ham J, Blomquist H, Bagge O, Alexandersson E, Ortiz R (2019) High-throughput field-phenotyping tools for plant breeding and precision agriculture. *Agronomy* 9(5): 258.

Chou LM, Yeemin T, Yaman ARBG, Vo ST, Alino P (2009) Coral reef restoration in the South China Sea. *Galaxea* 11(2): 67-74.

Chou LM, Toh TC, Toh KB, Ng CSL, Cabaitan P, Tun K, *et al.* (2016) Differential response of coral assemblages to thermal stress underscores the complexity in predicting bleaching susceptibility. *PLoS One* e0159755.

Claar DC, Tietjen KL, Cox KD, Gates RD, Baum JK (2020) Chronic disturbance modulates symbiont (Symbiodiniaceae) beta diversity on a coral reef. *Scientific Reports* 10(1): 4492.

Clements CS, Hay ME (2019) Biodiversity enhances coral growth, tissue survivorship and suppression of macroalgae. *Nature Ecology and Evolution* 3(2): 178-182.

Collin A, Planes S (2012) Enhancing coral health detection using spectral diversity indices from world- view-2 imagery and machine learners. *Remote Sensing* 4(10): 3244-3264.

Contardi M, Fadda M, Isa V, Louis YD, Madaschi A, Vencato S, *et al.* (2023) Biodegradable zein-based biocomposite films for underwater delivery of curcumin reduce thermal stress effects in corals. *ACS Applied Materials & Interfaces* 15(28): 33916-33931.

Cook N, Cook K, Harris KJ, Songcuan A, Smith AK, (2023). Lessons learned implementing mineral accretion and coral gardening at Agincourt Reef, Great Barrier Reef. *Ecological Management and Restoration* 24(2-3): 107-118.

Craggs J, Guest JR, Davis M, Simmons J, Dashti E, Sweet M (2017) Inducing broadcast coral spawning *ex situ*: closed system mesocosm design and husbandry protocol. *Ecology and Evolution* 7(24): 11066-11078.

Cross AT, Pedrini S, Kingsley WD (2020) Foreword: international standards for native seeds in ecological restoration. *Restoration Ecology* 28: S216-S218.

Damjanovic K, Blackall LL, Webster NS, van Oppen MJH (2017) The contribution of microbial biotechnology to mitigating coral reef degradation. *Microbial Biotechnology* 10(5): 1236.

Dehnert I, Saponari L, Galli P, Montano S (2022) Comparing different farming habitats for mid-water rope nurseries to advance coral restoration efforts in the Maldives. *PeerJ* 10: e12874.

de Campos BG, Figueiredo J, Perina F, Moledo de Souza Abessa D, Loureiro S, Martins R (2022) Occurrence, effects and environmental risk of antifouling biocides (EU PT21): are marine ecosystems threatened? *Critical Reviews in Environmental Science and Technology* 52(18): 3179-3210.

de la Cruz DW, Villanueva RD, Baria MVB (2014) Community-based, low-tech method of restoring a lost thicket of *Acropora* corals. *ICES Journal of Marine Science* 71(7): 1866-1875.

de la Cruz DW, Harrison PL (2017) Enhanced larval supply and recruitment can replenish reef corals on degraded reefs. *Scientific Reports* 7(1): 1-13.

Dennison WC, Barnes DJ (1988) Effect of water motion on coral photosynthesis and calcification. *Journal of Experimental Marine Biology and Ecology* 115(1): 67-77.

Dizon RM, Edwards AJ, Gomez ED (2008) Comparison of three types of adhesives in attaching coral transplants to clam shell substrates. *Aquatic Conservation: Marine and Freshwater Ecosystems* 18(7): 1140-1148.

Doering T, Wall M, Putchim L, Rattanawongwan T, Schroeder R, Hentschel U, *et al.* (2021) Towards enhancing coral heat tolerance: a "microbiome transplantation" treatment using inoculations of homogenized coral tissues. *Microbiome* 9(1): 102.

Doropoulos C, Vons F, Elzinga J, Hofstede RT, Salee K, Koningsveld MV, *et al.* (2019) Testing industrial-scale coral restoration techniques: harvesting and culturing wild coral-spawn slicks. *Frontiers in Marine Science* 6: 658.

Duarte CM, Agusti S, Barbier E, Britten GL, Castilla JC, Gattuso JP, *et al.* (2020) Rebuilding marine life. *Nature* 580(7801): 39-51.

Engelhardt KE, Vetter J, Wöhrmann-Zipf F, Dietzmann A, Proll FM, Reifert H, *et al.* (2023) Contact-free impacts of sessile reef organisms on stony coral productivity. *Communications Earth and Environment* 4(1): 396.

Fawad IA, Ullah A, Choi W (2023) Machine learning framework for precise localization of bleached corals using bag-of-hybrid visual feature classification. *Scientific Reports* 13(1): 19461.

Ferse SCA, Hein MY, Rölfer L (2021) A survey of current trends and suggested future directions in coral transplantation for reef restoration. *PLoS ONE* e0249966.

Ferreira V, Pavlaki MD, Martins R, Monteiro MS, Maia F, Tedim J, *et al.* (2021) Effects of nanostructure antifouling biocides towards a coral species in the context of global changes. *Science of the Total Environment* 799: 149324.

Ferrier-Pagès C, Witting J, Tambutté E, Sebens KP (2003) Effect of natural zooplankton feeding on the tissue and skeletal growth of the scleractinian coral *Stylophora pistillata*. *Coral Reefs* 22: 229-240.

Foo SA, Asner GP (2019) Scaling up coral reef restoration using remote sensing technology. *Frontiers in Marine Science* 13: 6.

Foo SA, Asner GP (2020) Sea surface temperature in coral reef restoration outcomes. *Environmental Research Letters* 15(7): 074045.

Forsman ZH, Page CA, Toonen RJ, Vaughan D (2015) Growing coral larger and faster: micro-colony-fusion as a strategy for accelerating coral cover. *PeerJ* 3: e1313.

Gabay Y, Parkinson JE, Wilkinson SP, Weis VM, Davy SK (2019) Inter-partner specificity limits the acquisition of thermotolerant symbionts in a model cnidarian-dinoflagellate symbiosis. *The ISME Journal* 13(10): 2489-2499.

Gonzalez-Rivero M, Beijbom O, Rodriguez-Ramirez A, Bryant DEP, Ganase A, Gonzalez-Marrero Y, *et al.* (2020) Monitoring of coral reefs using artificial intelligence: a feasible and cost-effective approach. *Remote Sensing* 12(3): 489.

Goreau TJ (2014) Electrical stimulation greatly increases settlement, growth, survival, and stress resistance of marine organisms. *Natural Resources* 5: 527-537.

Goreau TJF, Prong P (2017) Biorock electric reefs grow back severely eroded beaches in months. *Journal of Marine Science and Engineering* 5(4): 48.

Guest JR, Baria-Rodriguez MV, Toh TC, de la Cruz D, Vicentuan K, Gomez E, *et al.* (2023) Live slow, die old: larval propagation of slow-growing, stress-tolerant corals for reef restoration. *Coral Reefs* 42: 1365-1377.

Guest JR, Dizon RM, Edwards AJ, Franco C, Gomez ED (2011) How quickly do fragments of coral "self-attach" after transplantation? *Restoration Ecology* 19(2): 234-242.

Hamylton SM, Zhou Z, Wang L (2020) What can artificial intelligence offer coral reef managers? *Frontiers in Marine Science* 7: 603829.

Harrison PL (2011) Sexual reproduction of scleractinian corals. In *Coral Reefs: An Ecosystem in Transition*. Dubinsky Z, Stambler N (eds) Springer, Dordrecht. pp: 59-85.

Harrison PL, Villanueva RD, de la Cruz DW (2016) Coral reef restoration using mass coral larval reseeding. Final Report to Australian Centre for International Agricultural Research, Project SRA FIS/2011/031. Canberra.

Henry JA, O'Neil KL, Patterson JT (2019) Native herbivores improve sexual propagation of threatened staghorn coral *Acropora cervicornis*. *Frontiers in Marine Science* 6: 713.

Hernández-Delgado EA, Mercado-Molina AE, Alejandro-Camis PJ, Candelas-Sánchez F, Fonseca-Miranda JS, González-Ramos CM, *et al.* (2014) Community-based coral reef rehabilitation in a changing climate: lessons learned from hurricanes, extreme rainfall, and changing land use impacts. *Open Journal of Ecology* 4(14): 918.

Hernández-Delgado EA, Mercado-Molina AE, Suleimán Ramos SE (2018) Multi-disciplinary lessons learned from low-tech coral farming and reef rehabilitation: I. Best management practices. *Corals in Changing World*. Duque C, Tello Camacho E (eds), InTech, Croatia. pp: 213-244.

Hoadley KD, Lockridge G, McQuagge A, Pahl KB, Lowry S, Wong S, *et al.* (2023) A phenomic modeling approach for using chlorophyll-a fluorescence-based measurements on coral photosymbionts. *Frontiers in Marine Science* 10: 1092202.

Howells EJ, Abrego D, Liew YJ, Burt JA, Meyer E, Aranda M (2021) Enhancing the heat tolerance of reef-building corals to future warming. *Science Advances* 7(34): eabg6070.

Huang YL, Mayfield AB, Fan TY (2020) Effects of feeding on the physiological performance of the stony coral *Pocillopora acuta*. *Scientific Reports* 10: 19988.

Huffmyer AS, Johnson CJ, Epps AM, Lemus JD, Gates RD (2021) Feeding and thermal conditioning enhance coral temperature tolerance in juvenile *Pocillopora acuta*. *Royal Society Open Science* 8(5): 210644.

Hughes TP, Baird AH, Morrison TH, Torda G (2023) Principles for coral reef restoration in the Anthropocene. *One Earth* 6(6): 656-665.

Hughes TP, Kerry JT, Álvarez-Noriega M, Álvarez Romero JG, Anderson KD, Baird AH, *et al.* (2017) Global warming and recurrent mass bleaching of corals. *Nature* 543(7645): 373-377.

Humanes A, Beauchamp EA, Bythell JC, Carl MK, Craggs JR, Edwards AJ, *et al.* (2021) An experimental framework for selectively breeding corals for assisted evolution. *Frontiers in Marine Science* 8: 626.

Jamil S, Rahman M, Haider A (2021) Bag of features (BoF) based deep learning framework for bleached corals detection. *Big Data and Cognitive Computing* 5(4): 53.

Jayanthi M, Samynathan M, Thirumurthy S, Kumararaja P, Muralidhar M, Vijayan KK (2021). Mapping coastal lagoon characteristics for the aquaculture suitability using multi-criteria decision support (MCDS) spatial analysis: a case study from South-East coast of India. *Journal of Earth System Science* 130: 1-14.

Jordaan G, Umenne P (2021) Marine aquarium temperature controller and the IoT (Internet of Things). In 2021 International Conference on Artificial Intelligence, Big Data, Computing and Data Communication Systems (icABCD), pp. 1-7.

Kamruzzaman SY, Sakib FS, Rahman LM, Ahmed T, Alam S, Shakir MB, *et al.* (2022). Sense-IT: an aquaculture-specific autonomous data acquisition and monitoring system. In 2022 International Electronics Symposium (IES), pp. 404-409.

Knapp ISS, Forsman ZH, Greene A, Johnston EC, Bardin CE, Chan N, *et al.* (2022) Coral micro-fragmentation assays for optimizing active reef restoration efforts. *PeerJ* 10: e13653.

Klepac CN, Eaton KR, Petrik CG, Arick LN, Hall ER, Muller EM (2023) Symbiont composition and coral genotype determine massive coral species performance under end-of-century climate scenarios. *Frontiers in Marine Science* 14: 10.

Koren K, Jakobsen SL, Kühl M (2016) *in vivo* imaging of O2 dynamics on coral surfaces spray-painted with sensor nanoparticles. *Sensors and Actuators B: Chemical* 237: 1095-1101.

Leal MC, Ferrier-Pagès C, Petersen D, Osinga R (2016) Coral aquaculture: applying scientific knowledge to *ex situ* production. *Reviews in Aquaculture* 8(2): 136-153.

Levy G, Shaish L, Haim A, Rinkevich B (2010) Mid water rope nursery-testing design and performance of a novel reef restoration instrument. *Ecological Engineering* 36(4): 560-569.

Ligson CA, Cabaitan PC, Harrison PL (2022) Survival and growth of coral recruits in varying group sizes. *Journal of Experimental Marine Biology and Ecology* 556: 151793.

Lippmann RB, Helmstedt KJ, Gibbs MT, Corry P (2023) Optimizing facility location, sizing, and growth time for a cultivated resource: a case study in coral aquaculture. *PLoS ONE* e0282668.

Lirman D, Schopmeyer S (2016) Ecological solutions to reef degradation: optimizing coral reef restoration in the Caribbean and Western Atlantic. *PeerJ* 4: e2597.

Liu PJ, Chang HF, Mayfield AB, Lin HJ (2020) Influence of the seagrass *Thalassia hemprichii* on coral reef mesocosms exposed to ocean acidification and experimentally elevated temperatures. *Science of the Total Environment* 700: 134464.

Liu PJ, Lin SM, Fan TY, Meng PJ, Shao KT, Lin HJ (2009) Rate of overgrowth by macroalgae and attack by sea anemones are greater for live coral than dead coral under conditions of nutrient enrichment. *Limnology and Oceanography* 54: 1167-1175.

Lohr KE, Bejarano S, Lirman D, Schopmeyer S, Manfrino C (2015) Optimizing the productivity of a coral nursery focused on staghorn coral *Acropora cervicornis*. *Endangered Species Research* 27(3): 243-250.

Low NHN, Ng CA, Micheli F (2020) A low-cost modular control system for multi-stressor experiments. *Limnology and Oceanography: Methods* 18(10): 623-634.

Lumini A, Nanni L, Maguolo G (2020) Deep learning for plankton and coral classification. *Applied Computing and Informatics* 19(3/4): 265-283.

Macadam A, Nowell CJ, Quigley K (2021) Machine learning for the fast and accurate assessment of fitness in coral early life history. *Remote Sensing* 13(16): 3173.

Mahmood A, Bennamoun M, An S, Sohel F, Boussaid F, Hovey R, *et al.* (2017) Deep learning for coral classification. In *Handbook of Neural Computation,* Academic Press, pp. 383-401.

Mayfield AB (2022) Machine-learning-based proteomic predictive modeling with thermally challenged Caribbean reef corals. *Diversity* 14: 33.

Mayfield AB, Dempsey AC, Chen CS, Lin C (2022a) Expediting the search for climate-resilient reef corals in the Coral Triangle with artificial intelligence. *Applied Sciences* 12: 12955.

Mayfield AB, Dempsey AC, Chen CS (2022b) Predicting the abundance of corals from simple environmental predictors with a machine-learning approach. *Platax* 19: 1-24.

Merck DE, Petrik CG, Manfroy AA, Muller EM (2022) Optimizing seawater temperature conditions to increase the productivity of *ex situ* coral nurseries. *PeerJ* 10: e13017.

Miller MW, Latijnhouwers KRW, Bickel A, Mendoza Quiroz S, Schick M, Burton K, *et al.* (2022) Settlement yields in large-scale *in situ* culture of Caribbean coral larvae for restoration. *Restoration Ecology* 30: e13512.

Montano S, Dehnert I, Seveso D, Maggioni D, Montalbetti E, Strona G, *et al.* (2022) Effects of the COVID-19 lockdowns on the management of coral restoration projects. *Restoration Ecology* 30(8): e13646.

Montseny M, Linares C, Viladrich N, Capdevila P, Ambroso S, Diaz D, *et al.* (2020) A new large-scale and cost-effective restoration method for cold-water coral gardens. *Aquatic Conservation: Marine and Freshwater Ecosystems* 30(5): 977-987.

Moretti M, Hountondji M, Ge R, Emwas AH, Bilalis P, Susapto HH, *et al.* (2023) Selectively positioned catechol moiety supports ultrashort self-assembling peptide hydrogel adhesion for coral restoration. *Langmuir* 39(49): 17903-17920.

Moura A, Beck B, Duffey R, McEachron L, Miller M, Moore J, *et al.* (2021) Integrating coral restoration data with a novel coral sample registry. *Frontiers in Marine Science* 8: 700172.

National Academies of Sciences, Engineering, and Medicine (2019) *A Decision Framework for Interventions to Increase the Persistence and Resilience of Coral Reefs.* The National Academies Press, Washington, DC.

Neil RC, Barton JA, Dougan W, Dworjanyn S, Heyward A, Mos B, *et al.* (2024) Size matters: micro herbivores make a big impact in coral aquaculture. *Aquaculture* 581: 740402.

Nedimyer K, Gaines K, Roach S (2011) "Coral Tree Nursery©:" an innovative approach to growing corals in an ocean-based field nursery." *Aquaculture, Aquarium, Conservation & Legislation* 4(4): 442-446.

O'Neil KL (2015) Land-based coral nurseries: avaluable tool for production and transplantation of *Acropora cervicornis.* M.S. thesis, NOVA Southeastern University (USA).

Parkinson JE, Bartels E, Devlin-Durante MK, Lustic C, Nedimyer K, Schopmeyer S, *et al.* (2018) Extensive transcriptional variation poses a challenge to thermal stress biomarker development for endangered corals. *Molecular Ecology* 27(5): 1103-1119.

Platz MC, Takeshita Y, Bartels E, Arias ME (2020) Evaluating the potential for autonomous measurements of net community production and calcification as a tool for monitoring coral restoration. *Ecological Engineering* 158: 106042.

Ponce DN (2023) Optimization of light spectrum during coral grow-out. M.S. thesis, NOVA Southeastern University (USA).

Poquita-Du RC, Toh KB, Toh TC, Ng CSL, Taira D, Loke HX, *et al.* (2017) Effects of nursery table slope orientation on coral survival and growth. *Marine Biology Research* 13(9): 975-982.

Punt AE (2017) Strategic management decision-making in a complex world: quantifying, understanding, and using trade-offs. *ICES Journal of Marine Science* 74(2): 499-510.

Putnam HM, Barott KL, Ainsworth TD, Gates RD (2017) The vulnerability and resilience of reef-building corals. *Current Biology* 27(11): R528-R540.

Putnam HM, Ritson-Williams R, Cruz JA, Davidson JM, Gates RD (2020) Environmentally-induced parental or developmental conditioning influences coral offspring ecological performance. *Scientific Reports* 10(1): 13664.

Quiroz SM, Beltrán-Torres AU, Grosso-Becerra MV, Villareal DM, Rentería RT, Banaszak AT (2023) Long- term survival, growth, and reproduction of *Acropora palmata* sexual recruits outplanted onto Mexican Caribbean reefs. *PeerJ* 11: e15813.

Randall CJ, Giuliano C, Allen K, Bickel A, Miller M, Negri AP (2022) Site mediates performance in a coral-seeding trial. *Restoration Ecology* 31(3): e13745.

Randall CJ, Giuliano C, Heyward AJ, Negri AP (2021) Enhancing coral survival on deployment devices with microrefugia. *Frontiers in Marine Science* 8: 662263.

Ridlon AD, Grosholz ED, Hancock B, Miller MW, Bickel A, Froehlich HE, *et al.* (2023) Culturing for conservation: the need for timely investments in reef aquaculture. *Frontiers in Marine Science* 10: 1069494.

Rinkevich B (2014) Rebuilding coral reefs: does active reef restoration lead to sustainable reefs? *Current Opinion in Environmental Sustainability* 7: 28-36.

Rinkevich B (1995) Restoration strategies for coral reefs damages by recreational activities: the use of sexual and asexual recruits. *Restoration Ecology* 3: 241-251.

Rocha RJ, Pimentel T, Serôdio J, Rosa R, Calado R (2013) Comparative performance of light emitting plasma (LEP) and light emitting diode (LED) in *ex situ* aquaculture of scleractinian corals. *Aquaculture* 402: 38-45.

Roepke LK, Brefeld D, Soltmann U, Randall CJ, Negri AP, Kunzmann A (2022) Antifouling coatings can reduce algal growth while preserving coral settlement. *Scientific Reports* 12: 15935.

Roger L, Lewinski N, Putnam H, Chen S, Roxbury D, Tresguerres M, *et al.* (2023) Nano-technology for coral reef conservation, restoration and rehabilitation. *Nature Nanotechnology* 18: 831-833.

Romatzki SBC (2014) Influence of electrical fields on the performance of *Acropora* coral transplants on two different designs of structures. *Marine Biology Research* 10: 449-459.

Rosado PM, Cardoso PM, Rosado JG, Schultz J, Nunes da Rocha U, Keller-Costa T, *et al.* (2023) Exploring the potential molecular mechanisms of interactions between a probiotic consortium and its coral host. *Msystems* 8(1): e00921-22.

Sabater MG, Yap HT (2002) Growth and survival of coral transplants with and without electrochemical deposition of CaCO3. *Journal of Experimental Marine Biology and Ecology* 272(2): 131-146.

Sabater MG, Yap HT (2004) Long-term effects of induced mineral accretion on growth, survival and corallite properties of *Porites cylindrica* Dana. *Journal of Experimental Marine Biology and Ecology* 311(2): 355-374.

Sam SQ, Ng CSL, Kikuzawa YP, Toh TC, Sim WT, Chou LM (2021) Influence of fragment size on post transplantation growth and survival of domed scleractinian corals. *Marine Biology Research* 17(4): 327-340.

Schmidt-Roach S, Duarte CM, Hauser CAE, Aranda M (2020) Beyond reef restoration: next-generation techniques for coral gardening, landscaping, and outreach. *Frontiers in Marine Science* 7: 672.

Schmidt-Roach S, Klaus R, Al-Suwailem AM, Prieto AR, Charrière J, Hauser CAE, *et al.* (2023) Novel infrastructure for coral gardening and reefscaping. *Frontiers in Marine Science* 10: 202.

Schopmeyer SA, Lirman D, Bartels E, Byrne J, Gilliam DS, Hunt J, *et al.* (2012). *in situ* coral nurseries serve as genetic repositories for coral reef restoration after an extreme cold-water event. *Restoration Ecology* 20(6): 696-703.

Schultz J, Modolon F, Rosado AS, Voolstra CR, Sweet M, Peixoto RS (2022) Methods and strategies to uncover coral-associated microbial dark matter. *Msystems* 7(4): e00367-22.

Sellares-Blasco RI, Villalpando MF, Guendulain-García SD, Croquer A (2021) Assisted coral reproduction in the Dominican Republic: a successful story to replicate in the Caribbean. *Frontiers in Marine Science* 8: 669505.

Shafir S, Abady S, Rinkevich B (2009) Improved sustainable maintenance for mid-water coral nursery by the application of an anti-fouling agent. *Journal of Experimental Marine Biology and Ecology* 368(2): 124-128.

Shaish L, Levy G, Gomez E, Rinkevich B (2008) Fixed and suspended coral nurseries in the Philippines: establishing the first step in the "gardening concept" of reef restoration. *Journal of Experimental Marine Biology and Ecology* 358(1): 86-97.

Shaver EC, McLeod E, Hein MY, Palumbi SR, Quigley K, Vardi T, *et al.* (2022). A roadmap to integrating resilience into the practice of coral reef restoration. *Global Change Biology* 28(16): 4751-4764.

Sineau M, Blouki M (2020) Increasing coral biomass using Biorock method in Chabahar Bay. *Journal of Marine Science and Technology* 19(2): 52-61.

Slagel S, Lohr K, O'Neil K, Patterson J (2021) Growth, calcification, and photobiology of the threatened coral *Acropora cervicornis* in natural versus artificial light. *Zoo Biology* 40(3): 201-207.

Smith DT, Potgieter AB, Chapman SC (2021) Scaling up high-throughput phenotyping for abiotic stress selection in the field. *Theoretical and Applied Genetics* 134(6): 1845-1866.

Soong K, Chen T (2003) Coral transplantation: regeneration and growth of *Acropora* fragments in a nursery. *Restoration Ecology* 11(1): 62-71.

Spadaro AJ, Butler MJ (2021) Herbivorous crabs reverse the seaweed dilemma on coral reefs. *Current Biology* 31(4): 853-859.

Suggett DJ, van Oppen MJH (2022) Horizon scan of rapidly advancing coral restoration approaches for 21st century reef management. *Emerging Topics in Life Sciences* 6(1): 125-136.

Suggett DJ, Edmondson J, Howlett L, Camp EF (2020) Coralclip®: a low-cost solution for rapid and targeted out-planting of coral at scale. *Restoration Ecology* 28(2): 289-296.

Suggett DJ, Nitschke MR, Hughes DJ, Bartels N, Camp EF, Dilernia N, *et al.* (2022) Toward bio-optical phenotyping of reef-forming corals using light-induced fluorescence transient-fast repetition rate fluorometry. *Limnology and Oceanography: Methods* 20(3): 172-191.

Suzuki G, Okada W, Yasutake Y, Yamamoto H, Tanita I, Yamashita H, *et al.* (2020) Enhancing coral larval supply and seedling production using a special bundle collection system "coral larval cradle" for large-scale coral restoration. *Restoration Ecology* 28(5): 1172-1182.

Suzuki G, Yamashita H, Kai S, Hayashibara T, Suzuki K, Iehisa Y, *et al.* (2013) Early uptake of specific symbionts enhances the post-settlement survival of *Acropora* corals. *Marine Ecology Progress Series* 494: 149-158.

Taira D, Toh TC, Ng CSL, Loke HX, Afiq-Rosli L, Cabaitan PC, *et al.* (2017) Relocating bleached *Platygyra sinensis* facilitates recovery from thermal stress during a minor bleaching event. *Marine and Freshwater Behavior and Physiology* 50(5-6): 375-385.

Takeuchi I, Yamashiro H, Gushi M (2019) Usage of UV curable oligomer-based adhesive agent in hermatypic coral experimental research. *MethodsX* 6: 1600-1607.

Tebben J, Guest JR, Sin TM, Steinberg PD, Harder T (2014) Corals like it waxed: paraffin-based antifouling technology enhances coral spat survival. *PLoS One* e87545.

Ter Hofstede R, Elzinga J, Carr H, Koningsveld MV (2019) The coral engine: The way for local communities to sustainably produce corals for reef rehabilitation at a large scale. In Proceedings of 22nd World Dredging Congress and Exposition, WODCON 2019, pp. 772- 780. Chinese Dredging Association (CHIDA).

Toh TC, Ng CSL, Loke HX, Taira D, Toh KB, Afiq-Rosli L, *et al.* (2017) A cost-effective approach to enhance scleractinian diversity on artificial shorelines. *Ecological Engineering* 99: 349-357.

Toh TC, Ng CSL, Peh JWK, Toh KB, Chou LM (2014) Augmenting the post-transplantation growth and survivorship of juvenile scleractinian corals via nutritional enhancement. *PLoS One* e98529.

Tortolero-Langarica JJA, Rodríguez-Troncoso AP, Cupul-Magaña AL, Rinkevich B (2020) Micro-fragmentation as an effective and applied tool to restore remote reefs in the Eastern Tropical Pacific. *International Journal of Environmental Research and Public Health* 17(18): 6574.

Unsworth JD, Hesley D, D'Alessandro M, Lirman D (2021) Outplanting optimized: developing a more efficient coral attachment technique using Portland cement. *Restoration Ecology* 29(1): e13299.

van Oppen MJ, Gates RD, Blackall LL, Cantin N, Chakravarti LJ, Chan WY, *et al.* (2017) Shifting paradigms in restoration of the world's coral reefs. *Global Change Biology* 23(9): 3437-3448.

van Oppen MJ, Oliver JK, Putnam HM, Gates RD (2015) Building coral reef resilience through assisted evolution. *Proceedings of the National Academy of Sciences of the United States of America* 112(8): 2307-2313.

Voolstra CR, Suggett DJ, Peixoto RS, Parkinson JE, Quigley KM, Silveira CB, *et al.* (2021a) Extending the natural adaptive capacity of coral holobionts. *Nature Reviews Earth & Environment* 2(11): 747-762.

Voolstra CR, Valenzuela JJ, Turkarslan S, Cárdenas A, Hume BCC, Perna G, *et al.* (2021b) Contrasting heat stress response patterns of coral holobionts across the Red Sea suggest distinct mechanisms of thermal tolerance. *Molecular Ecology* 30(18): 4466-4480.

Wang C, Li Z, Wang T, Xu X, Zhang X, Li D (2021) Intelligent fish farm- the future of aquaculture. *Aquaculture International* 29(6): 2681-2711.

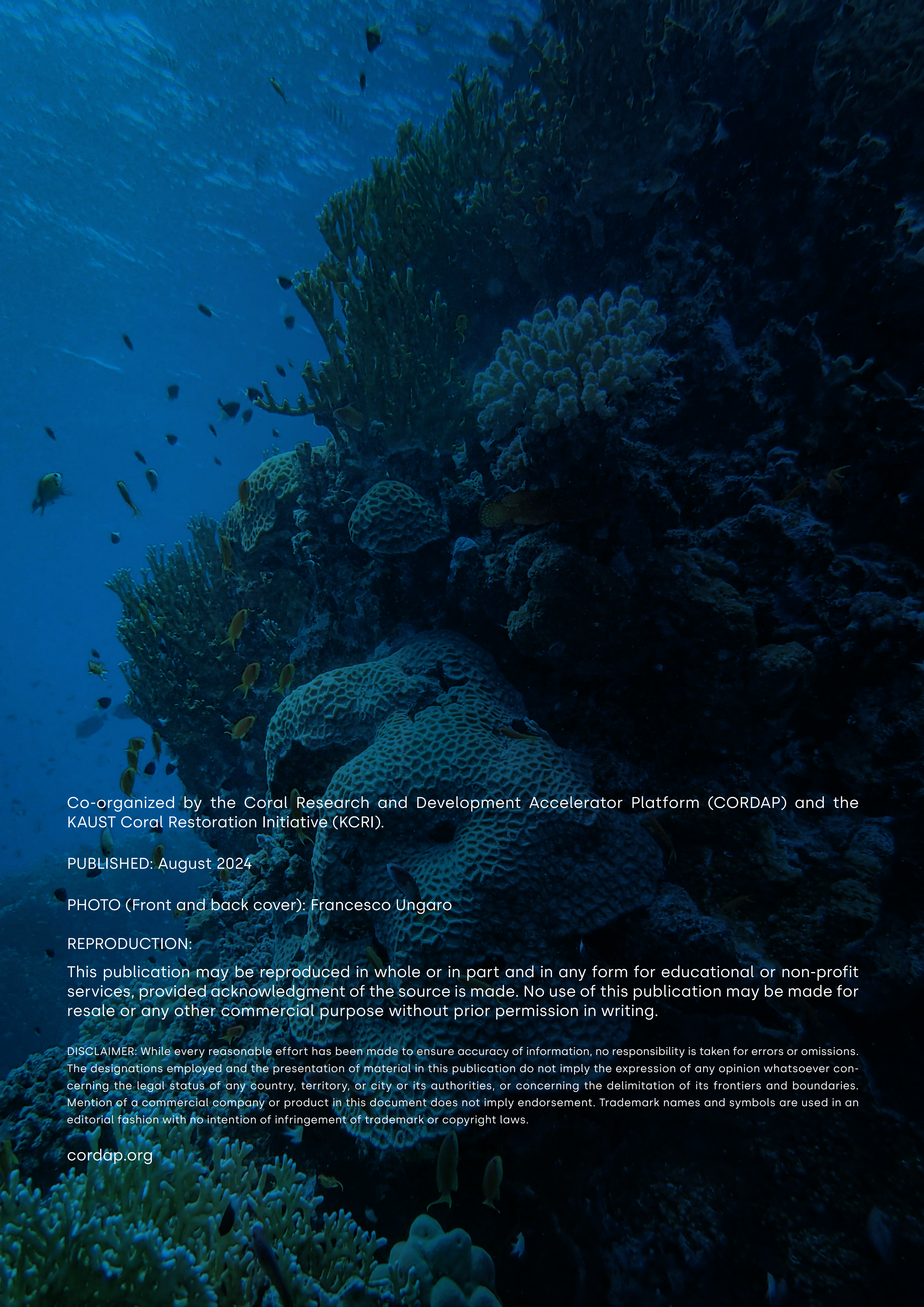
Wolfert S, Ge L, Verdouw C, Bogaardt MJ (2017) Big data in smart farming- a review. *Agricultural Systems* 153: 69-80.

Young BD, Serrano XM, Rosales SM, Miller MW, Williams D, Traylor-Knowles N (2020) Innate immune gene expression in *Acropora palmata* is consistent despite variance in yearly disease events. *PLoS One* e0228514.

Zhang Y, Barnes SJ, Kenkel CD (2022). Cross generational heritability analysis of physiological traits in *Porites astreoides* across an inshore-offshore gradient in the Lower Florida Keys. *Coral Reefs* 41(6): 1681-1692.

Zoccola D, Ounais N, Barthelemy D, Calcagno R, Gaill F, Henard S, *et al.* (2020) The World Coral Conservatory (WCC): a Noah's ark for corals to support survival of reef ecosystems. *PLoS Biology* e3000823.

Credit: Francesco Ungaro



Co-organized by the Coral Research and Development Accelerator Platform (CORDAP) and the KAUST Coral Restoration Initiative (KCRI).

PUBLISHED: August 2024

PHOTO (Front and back cover): Francesco Ungaro

cordap.org