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Analysis of the development of coral nurseries in Feridhoo island

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Abstract

Coral reefs are ecosystems just as diverse as fragile. Despite covering only a minimal portion of ocean and sea bottoms, an incredible diversity of species, both fauna and flora, directly depend on the well-being of this environment to hunt, feed, reproduce and prosper. For humans, reefs represent important coastal sheltering tools, fishing grounds and tourism attractions. Over the last five decades over half of the world's coral barriers have been lost with a subsequent disruption of the dependent biodiversity mainly due to stressors derived by human activity such as pollution, unregulated fishing and climate change. Awareness towards the conservation of these organisms has been increasing with the development of restoration techniques, both active and passive, aimed at recovering the damaged reefs. The Maldivian archipelago is characterized by over a thousand islands each possessing its own coral barrier. Numerous projects have been founded to safeguard its marine biodiversity, one of these being the Coral Restoration Program Feridhoo, a small independent project based on the isle of Feridhoo. This project has, since its foundation, adopted the nursery-based restoration technique where artificial structures are installed underwater as a growing and recovering ground for damaged coral fragments with the objective to grow samples able to survive and reproduce once transplanted back into the natural environment. This paper will cover the progress, difficulties, and successes achieved as well as displaying data collected on nursed fragments condition and growth. A comparison between structures is also performed by comparing key factors such as death and growth rate of housed corals. Even with a limited time frame due to the short-observed period a difference in performance between different nurseries has been observed.

1. Introduction

Corals are animals that first appeared 50 million years ago, during the Cambrian Period, the first geological phase of the Paleozoic Era. These marine invertebrates belong to the Phylum Cnidaria, Class Anthozoa. One of the characteristics of this Phylum, that includes soft and hard corals, jellyfish, hydrae and sea anemones, is the presence in the organisms of a specialized set of cells called cnidocytes (also known as cnidoblasts), used for capturing preys and among the most structurally complex cells known in the animal kingdom [27]. Each one of these cells consists of an organelle called cnida (or cnidocyst) and a trigger-like, mechanical, chemical and light receptor, called cnidocil, that once activated shoots the cnida outward. The specific sensory receptors genes responsible for their function remain unknown [1].

Every coral is the result of the settlement of single planula larvae which will grow to become a juvenile polyp. This individual will then start to develop into a colony via asexual reproduction, creating a group of genetically identical clones of itself and, in hard corals, develop a calcium carbonate skeleton holding all the newly developed polyps, each one housed in a bony cup called "corallite" [28]. The polyp anatomy is relatively simple: an interior hollow gastrovascular cavity is outlined by two layers of epidermis, on top of which a mouth surrounded by protruding tentacles connects the cavity to the external environment. An extracellular matrix, known as mesoglea, is found between the layers of epidermis, working as a hydrostatic skeleton and containing water, fibrous proteins, collagen, muscle bundles, nerve fibers and amoebocytes, the principal cellular defense element of Cnidaria [2]. Lastly, a thin layer of tissue, better known as coenosarc, connects adjacent polyps together [28].

Although they possess a mouth and are able to predate, up to 90% of energy required for survival, metabolism, growth and reproduction is provided by the mutualistic relationship between the coral and a symbiotic alga known as Zooxanthellae [27]. This alga is recruited by the animal and stored inside its epithelium where it produces energy by photosynthesis and, in return, receives protection, nutrients, carbon dioxide and an elevated position with access to sunshine [30]. Most corals can reproduce sexually (three quarters of all known species are hermaphrodite) in a synchronous mass spawning event where all species present in an area will release sperm and eggs at the same time. Male gametes swim to the surface to meet and fuse with female eggs forming an embryo that will search for the most suitable spot to settle based on noise, light levels and chemical stimulation [27].

Over 4000 species of corals have been discovered showing a great diversity of shapes, dimensions and colors. Based on these physical properties, hard corals have been divided into six major categories (massive, encrusting and foliose/laminar, free living, branching and columnar, corymbose, tabular), meanwhile soft corals have been divided into three (leathery, feathery, sea pumps), Each one of these morphologies holds its own advantages and disadvantages [28, 29].

Many hard coral colonies joint together may eventually form coral reefs, important underwater ecosystems, that are estimated to cover just 0.1% of the oceans' surface area and are found in the shallow coastal waters of the Pacific Ocean, Atlantic Ocean, Red Sea, Indian Ocean and Southeast Asia. This zone extends from approximately 30° N and 30° S of the equator where the optimal temperature of 26-27°C is more easily met [30]. Some deep-water corals have been discovered at a depth of over 2000m where the average temperature goes as low as 4°C and light is completely absent [31].

1.1. Ecosystem importance

Coral reefs house an incredible biodiversity with an approximate 25% of all marine species relying on them for nutrition, protection, nursery and habitat. Up to half a billion people worldwide directly depend on or benefit from the interactions with these ecosystems. Major fishing grounds are supported by reefs, where harvested species find a good feeding and reproductive ground [29]. The pharmaceutical sector has found in corals' chemical compounds great opportunities to develop new drugs that could greatly improve human diseases' treatment. For example, Diterpenes (a specific class of molecules isolated from corals) have shown to exhibit anti-inflammatory benefits [9], while newly discovered lobanes and cembranes showed a 50% inhibition of human tumor growth [9,10,11]. Coral reef related tourism provides great opportunities both in terms of employment and income to more than 100 jurisdictions all over the world with an approximate US$ 35.8B generated globally each year [3,6,12]. Finally, reefs play a key role in coastal protection, shielding land from the damaging effects of tropical storms and absorbing up to 97% of wave energy that would, otherwise, submerge entire coastal regions [4].

1.2. Threats to coral conservation

Despite their significance to humans and thousands of other species, corals are under constant threat due to an increasing number of factors. Climate change and global warming have caused ocean temperature to oscillate dangerously outside the optimal range of many marine species, including corals. Abnormal temperatures cause the expulsion of zooxanthellae, leading to the whitening, or bleaching, of the coral tissue and leaving the colony without their major source of energy. Rising sea levels and abnormal storm patterns reduce the amount of sunlight reaching the colonies and increase the raw power of waves that can destroy the reef structure. Ocean acidification, caused by the increase in carbon dioxide levels generated by combustion of fossil fuels, causes the formation of carbonic acid in the water which lowers the water's pH level, dissolving the coral skeleton and making it harder to rebuild [5,6]. Pollution and spreading of toxic chemicals end up disrupting the normal reproduction and growth cycles. Other man-caused threats include increased sedimentation, destructive fishing practices, irresponsible tourism and coral mining [6].

Even though they occur naturally, diseases and competition are other key elements that can endanger coral proliferation and survival and have been greatly exaggerated by man-made stressors. Although seemingly vast, suitable spots for settling and growing in the open waters are limited and intra and interspecific competition between reef species are concrete factors influencing these ecosystems equilibrium and biodiversity. Coral colonies need a rigid substratum to settle and expand on and, if the confining area is already occupied, aggression and fighting episodes may explode, potentially resulting in the death of one of the two colonies. Corals have been observed to compete with members of the same taxonomic family, anemone and a great variety of algae [7]. These episodes have demonstrated to negatively influence corals physiology causing severe abnormalities in the physical properties of the competing colony (compared to non-competing control individuals) due to great energy demands, such as: declined growth rate, abnormal symmetry shape, significant reduction in female gonads distribution per polyp, disruption of reproductive synchrony [8].

All the aforementioned stressors contribute to reducing and undermining the coral's natural defenses against already specialized pathogens that may take advantage of the colony's poor health. Some diseases (e.g. Brown Band Disease) have been observed to be the result of the natural interaction with predatory species, such as Parrotfish (*Scaridae Spp.*) or Crown-of-thorns Starfish (*Acanthaster Planci*) [13]. Despite increased research and scientific attention, most coral-related diseases' cause and mode of action remain unknown, impeding development of proper therapies [14], although a link between diseases and anthropomorphic stressors is statistically significant [15,16].

1.3. Human awareness and restoration

Since 1950, an approximate 50% of all coral reefs have been destroyed and 63% of coral-related biodiversity has been lost [17]. These numbers could increase to 90% in the next 20 to 30 years leading to a potential coral extinction by 2100 [18], with a consequent devastating loss of biodiversity and biomass. Awareness towards reefs' health was first raised by Charles Darwin when he observed that damaged coral fragments created by boat grounding or anchors would often die after drifting away from the original settling spot and being covered by sand [19]. He theorized that by securing the fragments back in place, not only they would recover but start growing as well.

During the 1970s, apprehension towards corals grew massively and, since then, focus on recovery and restoration has been progressively increasing between the scientific community, economic stakeholders and the general public, with more resources and labor being redirected towards the research of new and effective procedures. Nowadays, a general categorization of restoration techniques can be made by dividing them into two major categories: active and passive. Active techniques consist in the direct manipulation of shattered or diseased corals to increase the chances of recovery and regrowth, ranging from relatively simple and cheap methods (direct transplantation, gardening, substratum stabilization, etc. [21]) to more complicated and expensive alternatives (e.g., 3D printing of skeletal structures [22]). Passive techniques, such as enhanced biocontrol (e.g., introduction of algae-feeding herbivores, crown-of-thorns starfish population control, etc.), formulation of specific laws, creation of Marine Protected Areas etc., focus on removing coral-affecting stressors, hoping for the ecosystem to recover by itself [20, 26]. This can be performed either intentionally (with the mentioned methods) or unintentionally (e.g. Water and air quality improvement during the Covid-19 pandemic lockdown) [24, 25, 26].

Numerous governments, stakeholders and N.G.O.s recognized the importance of reefs and enacted dedicated laws and supporting programs aiding the tutelage of such ecosystems. One such initiative is the Coral Restoration Program Feridhoo (CRPF), founded as a means to protect and restore the Maldivian coral reef making use of the nursery technique. This method involves the underwater installation of coral supporting structures where broken coral shards are tied to, hoping for them to recover and grow. Once an optimal size has been reached, the colony can be placed back on its natural habitat.

2. Material and methods

The Coral Restoration Program Feridhoo (CRPF) was founded in early January 2022 with the intent of recovering and restoring the reef surrounding the island of Feridhoo (4°03'03"N 72°43'35"E), 47 nautical miles west of the capital Male, in the Republic of Maldives.

Figure 1 - GPS view of Feridhoo island

This small isle was surrounded by approximately 6200 m^2 of barrier reef, 30% of which has now been lost partially to the adverse and mutating climatic conditions and in part to the construction of the port and use of coral as a building material by the local community. The CRPF aims at enhancing and studying the efficiency of the already existing nursery techniques by observing and testing the effectiveness of different materials, water properties (such as depth, currents, light levels, etc.) and recovering properties of different coral species. The knowledge acquired but this study may, in the future, be applied to reef recovering programs in other islands of the Maldivian archipelago.

2.1. Nurseries

A nursery is an active restoration technique that functions by acting as a safe growing environment for damaged, diseased or displaced coral fragments collected from the sea floor [25]. Factors like shape, dimensions and location are decided based upon specific requirements and limitations of the chosen area, such as maximum housing capacity, most suitable building material, currents' and waves' strength, light levels, available anchoring spots and depth. Carefully planning the installation of the structures considering all these variables is crucial for maximizing the chances of coral recovery and growth. Corals are vulnerable to a multitude of stressors and without proper nursery design and site choice, growth and survival will be inhibited with the additional risk of wasting months of potential progress.

The effectiveness of nurseries has been proven several times over the course of different studies performed over a wide variety of coral species and locations [20, 32]. For example, corals grown on artificial structures during other studies have shown enhanced sexual reproduction, development of female gonads with consequent release of viable planula larvae at greater rates than natural colonies, bigger nursery-borne larvae with greater number of endosymbiotes and enhanced abilities to form colonies [23].

Since the start of the program, CRPF planted six structures of three different shapes on the east side of the island, an area that was adopted after receiving permission by local council authorities and evaluation of current strength and protection from storms. The adoption of not just a single shape was performed in order to conduct studies on which layout may bring beneficial effects on coral growth and housing and which, instead, may present issues or design flaws undermining the housed colonies' health or regrowth chances. The chosen structures are the following:

2.1.1. "Albero" or tree structure

The tree structure, placed on December 24th, is entirely made from PVC plastic and consists of a central vertical core from which eight horizontal arms protrude outwards resembling the shape of tree (and thus its name), a concrete dead-man anchor and fishing lines hanging from the arms. The whole tree is located 50 m offshore on the south side of the island with its dead-man anchor laying at a depth of around 10 meters on the angled sandy bottom. From top to bottom the core is 1,76 m long with four arms per side measuring 55 cm in length each and distanced 40 cm from one another. Each arm has a maximum housing capacity of 3 corals distant respectively 20, 15 and 10 cm from the core and fastened to a short rope which permits them to float instead of being directly secured to the structure, allowing for a grand total of 24 corals to be housed. The different height levels between arms allows to observe whether or not this factor affects coral recovery rate. The top portion of the core is connected through a 50 cm rope to a hollow plastic buoy which allows for the whole structure to stand vertically. An approximate 7 meters of water divide the buoy from the surface. Plastic numbered tags (numbered from 80 to 104) are applied above each coral fragment to easily record and keep track of growth and mortality rate as well as development of diseases and bleaching episodes. The overall structure has been designed to house primarily branching-type corals (e.g. *Acropora spp.*) since their particular shape grants them to be tied more effectively to the arms.

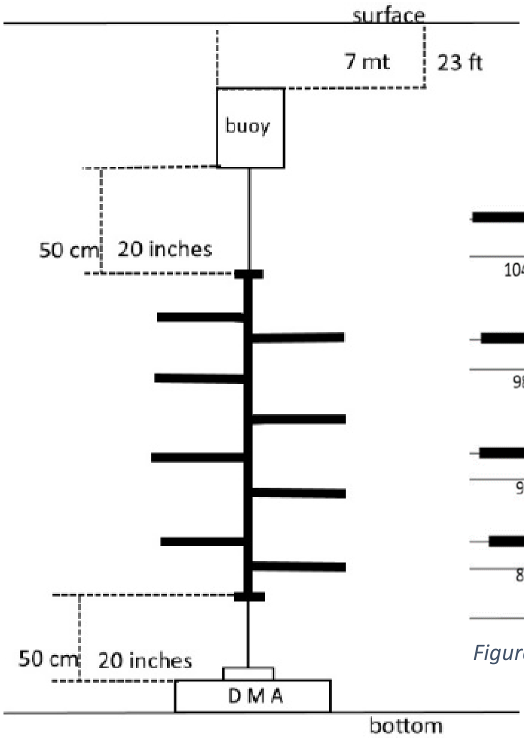

Figure 2 - Tree structural representation

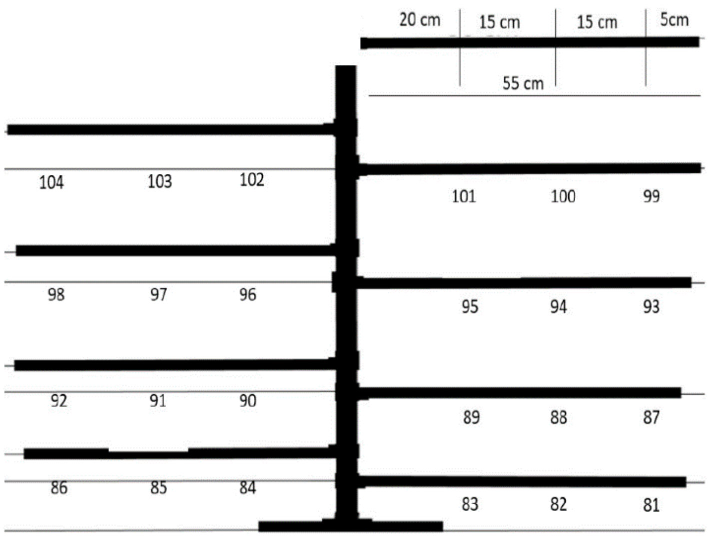

Figure 3 - Tree arms detail

2.1.2. "Stendino" or rank structure

The rank structure was placed on January 15th at a depth of 4,5 meters, 30 meters off the shore on the south side of the island and moved to a depth of 7 meter on a sandy bottom shortly after: a choice determined by the massive accumulation of algae both on the structure and coral fragments, a phenomenon that caused the death of every single colony housed.

This nursery is a 3,5 x 1,8 meters rectangle made from PVC plastic pipes and 8 racks made out of rope measuring 3,5 meters, each one distanced 20 cm from the next one. Each rack can house 10 coral fragments, one every 30 cm, secured by plastic zip-ties and numbered with plastic tags (from 1 to 80) to facilitate data record and monitoring. The hollow plastic chassis allows for the whole structure to float so a dead man anchor and ropes are used to keep it steady. Small fragments of different species and shapes can be housed since they are tied directly to the racks.

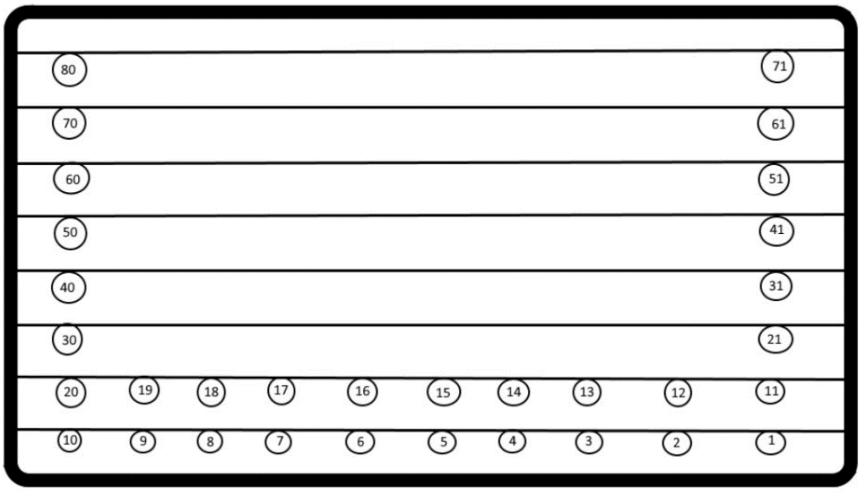

Figure 4 - Rake structural representation

2.1.3. Cone structure

The cone structure is a conic-shaped cage made entirely of iron bars welded together, composed by a hexagonal base and four horizontal levels distant 30 cm from each other reaching 90 cm in height all together. As of April 2023, 4 cones have been installed, with the first one being placed on January 16th 2022 and the latter three being placed on July 27th of the same year. On average, each cone is sitting at a depth of 5 meters, 30 meters offshore and placed on a rocky bottom, as close as possible to living native colonies and fish populations. These structures are not secured to any anchor whatsoever but are simply hammered down until the distal portion of the bars are partially underneath the sea floor.

The cones offer no limitation to coral species candidates to be housed since just like "stendino" each fragment is secured directly to the iron bars with a plastic zip-tie alongside a numbered tag to keep track and record of growth and mortality rates.

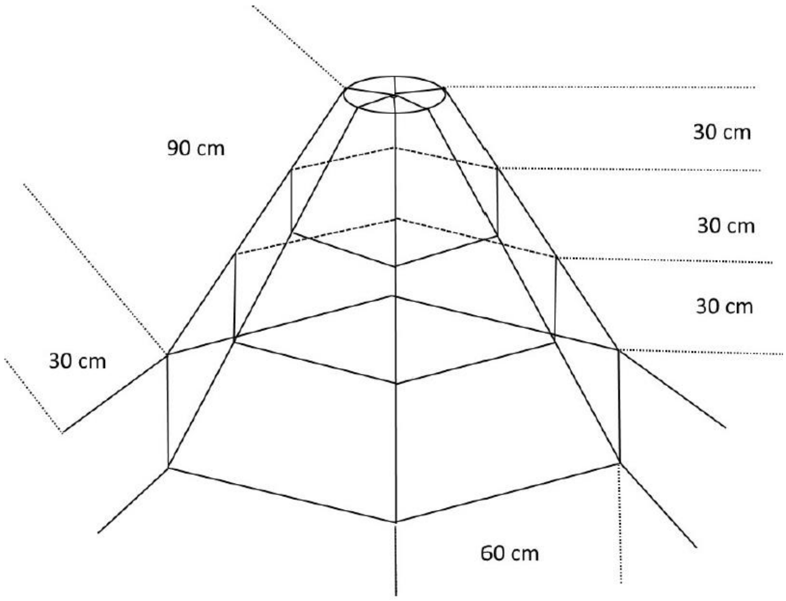

Figure 5 - Cone structural representation

2.2. Equipment and procedures

Collecting, sampling, measuring and moving coral fragments requires the user to spend a great amount of time underwater at depths ranging between 5 to 12 meters. An adequate training alongside the certified equipment is fundamental to meet any predetermined objective. Any diving sessions' duration is influenced primarily by the air reserve limitations and the goals set. On average up to 60 minutes are spent searching and collecting coral fragments from the seabed and another 90 minutes are spent applying the samples to the structure and/or performing maintenance routine. High-capacity air tanks (either 12- or 15-liters tanks at 200 atm pressure, supplying 2400 and 3000 liters of air respectively) are therefore needed alongside proper diving equipment. Although useful, a BCD (buoyancy control device) is not mandatory as the average working depth sits at around 6 meters (allowing for the altitude to be easily regulated by the user's own lungs air reserve) and the CRPF's researchers make extensive use of PETER diving system. This is an air supplying system that grants one or more users in tandem to be supplied from a surface-floating tank, thus facilitating diving operations by achieving a greater freedom of movement by neglecting the use of a BCD.

An array of different working tools is needed to perform all the tasks required, from collecting to cleaning. Coral collection, sampling and monitoring related tools include gloves, mesh bags, coral identification tables, 6” or 150 mm plastic calipers, underwater writing slates (for data collection), underwater camera, diving knife, plastic zip-ties, strings and number tags. Structure maintenance related tools include hard and soft brushes, steel wool, diving knife, spare number tags, fishing lines and zip-ties.

2.3. Coral collection

Although it is a relatively simple task, collecting adequate coral samples represents one of the most crucial phases of restoration as random or poorly performed sampling may negatively affect the outcome and potential of a single structure or even the whole project. Collecting, for example, a diseased or algae covered fragment and placing it on a structure already housing recovering colonies may cause said disease or algae to spread, potentially causing the death of the whole structure and wasting months’ worth of progress and data.

On that account, a series of ideal characteristics have been set for each sample to meet to be considered fit for collection. First, every fragment must not be collected directly from healthy corals as that may cause stress to the animal originating diseases, algae spread or bleaching episodes. Suitable samples are broken by natural causes, such as predation or damage caused by strong currents and waves and are found and collected from the sea floor. Ideally, a suitable candidate fragment presents a single break point, a healthy appearance displaying its natural colors, no algae coverage and no observable diseases and can be recognized at least at genus level. Corals that present predation wounds, friction damage or partial bleaching can be chosen as long as they don’t pose a threat to the integrity of other colonies. Ideal dimensions range between 3 to 15 cm as fragments below that range will hardly adhere to the nursery while those above cannot be stored in the mesh bags or measured efficiently.

Choosing different species is preferable as it increases both the genotypical and phenotypical pool on the structures and, because of transplantation, in the ecosystem. Still, the biggest portion of collected samples belong to the *Acropora* genus, in particular branching or staghorn type, as their particular tree-like shape makes them more vulnerable to snapping while making them compatible with every structure typology.

When a suitable fragment is found, it is collected in a mesh bag alongside other candidates and is carried with caution as improper handling may damage the animal. It is also important to avoid bringing fragments above surface or try to minimize their exposure to the terrestrial environment as the soft anatomy of the coral is not developed to tolerate surface air pressure and density causing the collapse of the polyp on its corallite. Time elapsing between collection and planting should never exceed 30 minutes to minimize capture-related stress.

2.4. Coral planting on housing nursery

As mentioned in the previous paragraph, the best nursery is typically chosen for each fragment based on their species-specific shape and dimensions. Samples are applied to the nursery using zip-ties or fishing lines and are always associated with a plastic number tag. Those who have been damaged during transport, do not fit steadily or are too difficult to tie can be discarded and placed back on the reef. Length measurements are then taken with a caliper and recorded on a writing slate. When working around any structure, caution must always be used so as not to damage the reef, the nursery itself or the coral present on it. Particular attention must be paid while acting on the cones since the surrounding area is rich of natural colonies that can be easily damaged by one's tools or fins.

2.5. General maintenance and monitoring

A regular checkup on all structures is performed once or twice every month in order to assess the health condition and growth progress of housed fragments, the nurseries' structural integrity and to assess the possible presence of damage caused by natural factors such as storms or predation.

All structures will build up an algae deposit (see figure 6) that if left unsupervised could spread to the fragments and potentially render the nursery useless for future applications. A deep and regular cleaning is therefore needed to keep each nursery at its maximum efficiency. Hard brushes and steel wool are used to scrape off any algae building up on the

PVC or iron portions while soft brushes or toothbrushes are used on ropes or strings. If possible, any structural issue encountered is fixed in situ.

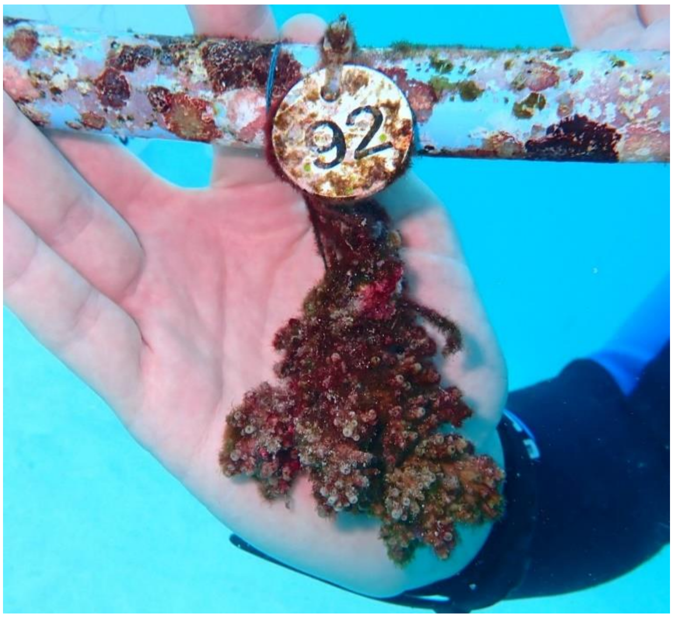

Figure 6 - Algae deposit on a coral and its housing structure

Corals' condition is assessed and noted by assigning a numerical value according to an evaluation score created by the researchers. The parameters observed are algae cover percentage, bleaching percentage and general health status (healthy, dead, ill).

For the first two parameters, a score ranging from 0 to 4 is assigned where 0 = 0% of algae or bleaching coverage, 1 = 0-25%, 2 = 25-50%, 3 = 50-75% and 4 = 75-100%. For health status, a score of 1 is given if the coral is alive, 2 if it's dead and 3 if it presents signs of disease. Dead corals are removed immediately and the date of death alongside the presumed cause is noted. A new fragment is then placed in its place. Corals that present evident signs of disease or partial algae coverage are left on the structure as long as they are still alive and the danger of spread to healthy fragments has been excluded, otherwise they are removed from the nursery.

2.6. Health and safety

The nature of the project and the type of work performed require meticulous planning to be performed to ensure that all operators can carry out their activities in the safest and most efficient way possible. Every island is characterized by a unique reef geography and by the archipelago's strong currents and fast changing weather. Having a member of the local community or an experienced guide as part of the team can have a considerable positive impact on the overall quality of work. Weather and current forecast should, nonetheless, be always checked before planning a dive.

Knowing the fauna and flora present around the working area can be helpful in identifying and avoiding dangers. For example, Feridhoo reefs present a discrete population of lionfish (genus *Pterois*) whose venom, used for predation, can have serious effects on human health. These fish have been observed swimming around working areas, probably attracted by the movement of sediment and, if not considered, can easily be led to attack. Other potentially dangerous animals such as moray eels, sharks, stingrays and Portuguese man o' wars (*Physalia physalis*) populate these waters. Understanding the correct way to operate in this ecosystem by respecting the local organisms can support maintaining a safe working environment.

Underwater currents can also become an obstacle when swimming, leading to increased fatigue and, consequently, increased air consumption and reduced maximum diving time. Losing or misplacing instruments and tools also becomes a risk. An adequate diving training allows for the researcher to promptly react to any changes and is therefore needed to guarantee efficiency and safety of any underwater operation.

3. Results and discussion

Since its foundation, Coral Restoration Project Feridhoo has produced interesting data on coral resilience by interaction with underwater nurseries. Moreover, a great quantity of observations on encountered issues and solutions implemented to fix them have been collected, extending the applicative knowledge in the field of coral restoration in the Maldivian archipelago. It is important to mention that, although affected by major complications, all structures were adopted as prototypes to experiment on a set of variables that affects coral growth and, still, some of them have grown to a size fitting for transplantation, living on the natural reef ever since. Difficulties encountered have therefore been analyzed not as major obstacles to the success of the operation but as opportunities to expand the applicative knowledge in the field of nursery-based coral restoration. Results on coral growth and well-being as well as single structure type performance and problems faced by the researchers will be discussed in the paragraphs that follow.

3.1. Issues with structures and solutions

The underwater environment proved to be the major issue as the rapidly growing algae and strong tides often caused great damage to the nurseries and to the housed corals. The building materials and location chosen for some of the structure also led to a significant spike in death rate of the fragments. One of the major problems recognized that affected all structures was the adoption of the plastic tag numeration system that favored algae spread significantly leading to coverage of fragments and portions of the nurseries. The plastic material also demonstrated to not be suitable to the underwater conditions, often leading to the tags breaking or being misplaced making data collection and progress tracking difficult. Individual solutions for each structure have since been applied. Some limitations were also found, primarily the lack of instrumentation able to measure water parameters crucial to coral growth such as salinity, light level, pH and chemical composition. These factors can change from one place to another around the island and at different depths leading to introduction of biases in the structures' performance analyses that can deem a nursery as inefficient although the result is not strictly related to its own shape.

The first ever installed cone, nicknamed "Cone D", was adopted as a prototype to experiment on the possible outcomes related to factors such as location, soil type, attachment method and coral behavior. A series of issues have since been observed and helped the researchers to develop improved methods and expand the knowledge regarding the subject. The fragments present on the structure faced a massive 50% death rate with 0% of fragments being completely healthy. The causes of such poor performance were credited to the inadequate installation area chosen characterized by a sandy bottom that caused fragments to be covered by sediment, favoring algae growth. On November 27^{th} the structure was removed, freed from all corals, cleaned and moved closer to the reef where it benefited from the higher water and illumination quality, presence of cleaner fish and lower residency of parrot fish (family Scaridae) that actively feed on corals. Since then, it received 60 fragments donated from the other nurseries. Another issue encountered within all cones (A, B, C, D) is the rapid formation of rust on the iron skeleton that can be countered by periodically scraping the structures with hard brushes. Whether or not the accumulation and presence of rust can affect the well-being of corals is yet to be determined. Lastly, although the focus of a nursery is to favor growth of housed colonies that will later be transplanted back to the natural reef, the cones represent an exception. Corals present on these structures have grown around and ultimately fused their skeleton with the metal bars that compose the cage, making them impossible to be removed for transplantation. Each cone has, therefore, become an artificial reef as well as a nursery.

"Albero", the tree structure, also went through trial and error and large variables were identified. For example, the sandy bottom of the initial installation site caused accumulation of sediment on corals favoring algae spread and bleaching episodes. The inclination level and lack of cleaner fish aggravated the process even further. The way in which the arms connected to the core also proved inappropriate to tolerate the strong underwater currents often causing the arms to detach and lay on the sand or being carried away with the subsequent loss of the correlated data. Due to these factors, on October 30th all fragments were removed from the nursery. Those in good health were either moved on to Cone D or planted back to the reef (if considered ready according to their size), whereas all dead or irreversibly diseased corals were discarded. On November 10th "Albero" was brought to shore, cleaned and its design was changed to house more corals and be more stable. From the layout visible on figure 2, the structure was changed into a DNA-like shape with 14 total arms. The numeration method was also modified. Each arm was given an alphabetical code and each coral a number that increases the further from the core it is located (for example: coral T.A1 refers to fragment 1, arm A of structure Tree). On November 21st the nursery was placed back into the water in a new area closer to the reef (see figure 7). Since then, new fragments were placed all belonging to the Acropora family. A new dead-man anchor has also been placed but did not receive its tree yet.

"Stendino", the rank structure, was severely affected by the poor location and water quality. The sedimentation of the sea floor caused continuous algae growth that led to a massive death rate among fragments with little to no help provided by the regular cleaning of the structure. Some of the corals went missing entirely, probably due to the action of parrot fish feeding on the fragments or underwater currents hitting the nursery, often leaving the plastic tag in place shifting its position along the rack, puzzling data collection even further. Healthy corals were partly relocated to Cone D or planted back to the reef. Similarly to "Albero", the structure was pulled out of water, cleaned and relocated. The tag numeration system was discarded in favor of a simpler sector-like division of the rakes. A series of knots were made thus creating sections each housing a single coral. With a maximum of 19 fragments per rake, the structure now holds 152 samples, all of which belong to the Pocillopora family.

In the next page, an image displaying all structures' updated locations can be found.

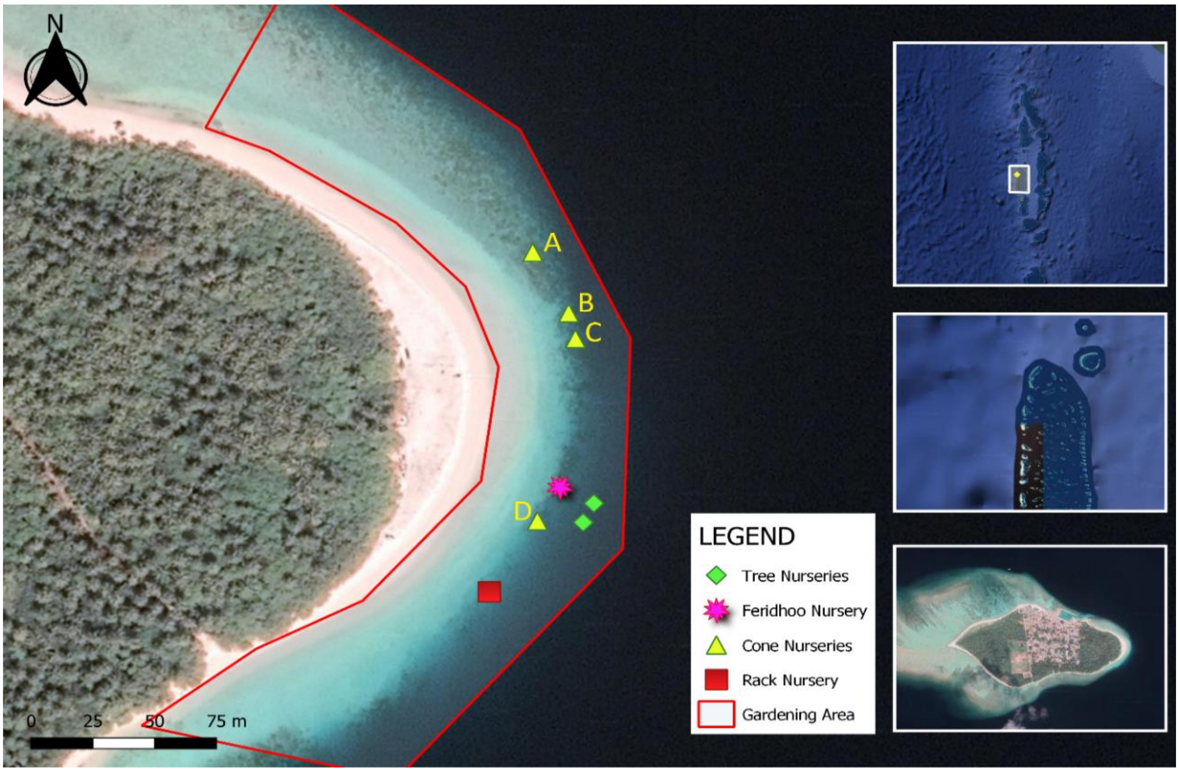

Figure 7 – GPS view of the updated structures' location

Note: The Feridhoo nursery refers to an iron bars structure welded in a way to spell the name of the island. Although its function is equal to that of the cones, as it works both as a nursery and an artificial reef, the structure has not been included in the same category. The reason behind this stands in the original purpose of the structure itself: the sign was installed with the help of the local council, community and tourists present on the island with the intent to raise awareness within the island's own population and, in the long term, promote its tourism.

Regardless of the fragments being cataloged, the data acquired from this structure will not be part of the present study and will not be considered in the overall outcome of the project.

3.2. Data collected on coral mortality, health and growth

The following sheets present nursed corals' growth and health status based on data collected from November 2022 to February 2023, a time range spanning from the month in which the fixes to the problems described in the previous paragraph were applied to the last up checkup and data update available to the author of this paper. Although this implies relinquishing all the information acquired in the previous months of work, analyzing the statistical output of said period would not benefit the overall conclusion of the study since the analyzed factor affecting coral growth (water and light quality, soil, algae accumulation, fauna present, etc.) were altered after the position and data collection system were changed.

As mentioned in paragraph 3.1, corals present on the cones ultimately fuse with the structure thus impeding their removal and relocation. For this reason, growth rate stopped being recorded on these structures, leaving health status and mortality rate as the only observed parameters.

3.2.1. Cones

Cone	Added	Fragments	Healthy	Dead	Unhealthy	Cause A	Cause B	Cause D	Cause AB	Mortality%	Healthy%
NOVEMBER CHECK - 26/11/2022											
A		56	50	2	4	3			1	4%	89%
B		40	36	1	3	3				3%	89%
C		40	39	0	1	1				0%	97%
D		57	55	0	2	2				0%	96%
DECEMBER CHECK - 19/12/2022											
A		52	41	3	8			5	3	6%	79%
B	10	49	43	2	4	1	2		1	4%	88%
C	10	50	39	4	7		5		2	8%	78%
D		57	50	3	4	2	1		1	5%	88%
JANUARY CHECK - 11/01/2023											
A	8	52	51	0	1	1				0%	98%
B		47	45	1	1	1				2%	96%
C		46	42	1	3	1	2			2%	91%
D		54	49	2	3	3				4%	91%
FEBRUARY CHECK - 16/02/2023											
A	8	60	50	4	6	3	2		1	3%	83%
B	4	49	43	2	4	2	2			4%	88%
C	5	50	45	0	5	1	3		1	0%	90%
D	8	58	46	5	7	4	2		1	9%	79%
AVERAGE											
CONE A										3,25%	87,25%
CONE B										3,25%	90,25%
CONE C										2,50%	89,00%
CONE D										4,50%	88,50%

Table 1 – Data visualization of cone structures

Before continuing with the analysis of the data displayed, it is important to make a premise: after the renovation of the cones and the decision to not collect information on individual fragments' growth, data collected refers exclusively to each structure as a whole, therefore only outlining the number of dead or diseased corals over the total. The different causes of illness are expressed as follows: A = algae cover, B = bleaching, D = disease, AB = both algae and bleaching. Four recording checks have been performed between November 2022 and February 2023, once a month. Each time, a percentage on death and health rate was calculated, allowing for an arithmetic average to be obtained indicating the gross performance of each cone over the 4-months period. The best and worst performing structures, respectively Cone B and Cone D, are highlighted in the table above. Cones A and C performed similarly to their neighbor. The difference in the parameters observed can be attributed to a series of hypothetical factors, the most plausible being the different geographical area chosen for the structures and the type of soil present. Cones A, B and C are collocated close to each other in an area rich in natural colonies on a primarily rocky bottom whereas Cone D lays in an area characterized by large sand areas which can cause the movement of sediment and cloudiness of the water.

3.2.2. "Albero"

ARM ID	CORALS	HEALTHY	DEAD	UNHEALTHY	ALGAE	BLEACHING	AVERAGE LENGHT	Δ LENGHT
NOVEMBER CHECK - 27/11/2022								
T.A	8	8	0	0	0	0	9,05 cm	/
T.B	8	8	0	0	0	0	9,15 cm	/
T.C	8	8	0	0	0	0	8,57 cm	/
T.D	8	8	0	0	0	0	9,47 cm	/
T.E	8	8	0	0	0	0	9,02 cm	/
T.F	8	8	0	0	0	0	9,42 cm	/
T.G	8	8	0	0	0	0	8,50 cm	/
T.H	8	8	0	0	0	0	9,42 cm	/
T.I	8	8	0	0	0	0	8,82 cm	/
T.J	8	8	0	0	0	0	8,55 cm	/
T.K	8	8	0	0	0	0	8,91 cm	/
T.L	8	8	0	0	0	0	9,16 cm	/
T.M	8	8	0	0	0	0	8,58 cm	/
T.N	8	8	0	0	0	0	9,22 cm	/
JANUARY CHECK - 10/1/2023								
T.A	8	7	0	1	1	0	9,77 cm	0,72 cm
T.B	8	7	0	1	1	0	9,76 cm	0,61 cm
T.C	8	8	0	0	0	0	9,28 cm	0,71 cm
T.D	8	8	0	0	0	0	9,72 cm	0,25 cm
T.E	8	6	1	1	1	0	9,34 cm	0,32 cm
T.F	8	7	1	0	0	0	9,92 cm	0,50 cm
T.G	8	7	0	1	1	0	8,98 cm	0,48 cm
T.H	8	6	1	1	1	1	9,7 cm	0,32 cm
T.I	8	8	0	0	0	0	9,15 cm	0,33 cm
T.J	8	7	0	1	1	0	8,82 cm	0,27 cm
T.K	8	6	2	0	0	0	8,71 cm	0,20 cm
T.L	8	8	0	0	0	0	9,27 cm	0,11 cm
T.M	8	7	1	0	0	0	8,67 cm	0,09 cm
T.N	8	5	1	2	1	0	9,42 cm	0,20 cm
FEBRUARY CHECK - 13/02/2023								
T.A	8	7	0	1	1	0	11,03 cm	1,26 cm
T.B	8	5	0	3	2	1	10,37 cm	0,61 cm
T.C	8	8	0	0	0	0	9,97 cm	0,69 cm
T.D	8	7	0	1	0	1	10,71 cm	0,99 cm
T.E	8	6	0	2	2	0	10,01 cm	0,67 cm
T.F	8	7	0	1	1	0	10,70 cm	0,78 cm
T.G	8	7	0	1	1	0	9,42 cm	0,44 cm
T.H	8	5	1	2	2	0	9,83 cm	0,13 cm
T.I	8	7	0	1	1	0	9,66 cm	0,51 cm
T.J	8	6	0	2	2	0	9,4 cm	0,58 cm
T.K	8	5	3	0	0	0	9,37 cm	0,66 cm
T.L	8	6	1	1	1	0	9,72 cm	0,45 cm
T.M	8	8	0	0	0	0	9,41 cm	0,74 cm
T.N	8	4	1	3	3	0	9,62 cm	0,20 cm
AVERAGE "ALBERO" PERFORMANCE								
Total fragments	125							
Total dead	13							
Mortality%	10.4%							
Average growth	0,49 cm/month							

Table 2 - Data visualization of tree structure

For the sake of simplicity of visualization, corals belonging to the same arm are not considered individually, meaning that, as reported in the table (ARM ID column where T = Tree), each arm is considered instead with a mean of the length of all corals belonging to each one of them. Three checks were performed on the structure in November 2022 and

January and February 2023 with recording on health status and length being performed every time. Thanks to the data acquired, an average growth rate per each arm can be calculated, grossly displaying the performance of each arm. The number of dead corals is also reported as well as diseased ones alongside the cause of illness. The total number of fragments per arm is always equal to 8 as dead corals are immediately changed with a new one. After four months “albero” performed with an average growth rate per month of 0,49 cm and a death rate of 10.4%.

3.2.3. “Stendino”

RACK ID	CORALS	HEALTHY	DEAD	UNHEALTHY	ALGAE	BLEACHING	AVERAGE LENGHT	Δ LENGHT
DECEMBER CHECK - 6/12/2022								
R.A	19	19	0	0	0	0	7,66 cm	/
R.B	19	19	0	0	0	0	8,18 cm	/
R.C	19	19	0	0	0	0	7,98 cm	/
R.D	19	19	0	0	0	0	7,62 cm	/
R.E	19	19	0	0	0	0	7,58 cm	/
R.F	19	19	0	0	0	0	7,49 cm	/
R.G	19	19	0	0	0	0	7,88 cm	/
R.H	19	19	0	0	0	0	8,04 cm	/
JANUARY CHECK - 10/1/2023								
R.A	19	16	0	3	3	0	8,19 cm	0,53 cm
R.B	19	15	0	4	4	0	8,68 cm	0,50 cm
R.C	19	16	0	3	0	0	8,23 cm	0,25 cm
R.D	19	16	0	3	0	0	7,78 cm	0,14 cm
R.E	19	14	0	5	0	0	8,02 cm	0,44 cm
R.F	19	16	0	3	2	1	7,78 cm	0,29 cm
R.G	19	14	0	5	5	0	8,29 cm	0,41 cm
R.H	19	17	0	2	2	0	8,27 cm	0,23 cm
FEBRUARY CHECK - 13/2/2023								
R.A	19	14	0	5	5	1	8,70 cm	0,51 cm
R.B	19	14	1	4	4	2	9,21 cm	0,53 cm
R.C	19	15	2	2	2	0	8,74 cm	0,51 cm
R.D	19	15	2	2	2	0	8,48 cm	0,60 cm
R.E	19	14	0	5	5	0	8,59 cm	0,57 cm
R.F	19	15	0	4	2	2	8,18 cm	0,30 cm
R.G	19	15	0	4	3	1	8,54 cm	0,25 cm
R.H	19	16	1	2	2	0	8,61 cm	0,34 cm
AVERAGE "STENDINO" PERFORMANCE								
Total fragments	158							
Total dead	6							
Mortality%	4%							
Average growth	0,40 cm/month							

Table 3 - Data visualization of rank structure

Similarly to table 2, the rank structure’s racks are evaluated individually instead of considering every single coral, so each rack is represented alongside the average length and growth compared to the previous check. On the table above, each rack is represented by an ID composed by the letter R (Rank) followed by a second letter indicating the line itself. The total number of fragments per rack is always equal to 19 as dead ones are replaced immediately after being recorded. After 3 months, "Stendino" performed with an average growth rate per month of 0,40 cm and a 4% death rate.

3.3. Determining the best structure based on data collected

Over the time frame studied and based on the data collected and performance of each structure, all nurseries produced promising results outlining their efficacy as a tool for coral reef restoration. Although fragile and susceptible to disease and death caused primarily by algae coverage, corals housed on the structures demonstrated to be able to positively interact with the new growing ground provided by the nursery [27] and recover to the point to be able to resume their growth with some even reaching a length and condition satisfactory enough for transplantation back into the reef.

By analyzing each structure's performance based on their data output, the best shape between the three adopted by the Coral Restoration Project Feridhoo could be determined to further develop its efficiency and to adopt it as the main nursery type for this kind of restoration methodology. By doing so, already efficient structures can be enhanced even further leading to a series of crucial benefits such as overall cost reduction, greater efficiency of deployment, increased success rates and greater output of recovered corals into the natural reef.

A statistical analysis would then be the most logical way to determine it. Unfortunately, an analysis based on the dataset provided by each structure could not be completed due to changes applied to the data collection methods (lack of data regarding growth rate in cones structures), biases introduced (planting of a single species per structure, namely *Acropora spp.* for "albero" and *Pocillopora spp.* for "stendino" that possess different natural growth rates) and limitations such as the lack of measuring tools able to detect specific water properties necessary to determine that the same characteristics are met in all nursing sites. Without a proper statistical analysis any conclusion made on whether a structure is superior to the others would be heavily influenced by such factors.

Despite this, the gathered data and results allow for some important conclusions to be made on which condition commonly shared between structures can favor or impede corals' growth. A significant difference in the rate of fragments death is notable between "albero" and other nurseries. When compared to the other growing sites, the tree structure's mortality rate rose above 10%, a figure 6 points higher to that of other structures. In particular, the arms located in the upper section of the structure (e.g. T.M and T.N) showed higher instances of illness, death and slower growth.

Logically, fragments located on a higher position should perform best since the greater light presence and lower sedimentation level favor growth consistently, a concept that, in this case, was not respected, thus leading to an indicative conclusion: an essential factor to coral growth is stability. The top section of "albero" often oscillated following the course of the island's strong current while the bottom, anchored to the concrete dead-man, favored from the more stable position. This hypothesis is further established when looking at the other nurseries' performance. "Stendino", a stable structure, only reached a death rate of 4% whereas the cones, extremely stable and with no soft or moving parts, set the bar even lower to 2.5-3.25%. An exception is made for cone D which fragments were donated not from the reef but from other structures, that suffered, for this reason, from the repetitive translocation. This factor further highlights the susceptibility of corals' fragile biology to movement-related stress demonstrating the importance of physical stability in coral restoration.

3.4. Future applications

An important aspect of any coral nursing project is to develop new and efficient ways to preserve and restore natural reefs or to enhance already existing ones. Sharing the knowledge acquired can help increase the chances of survival of adopted corals and, in the long term, help recover severely endangered ecosystems such as the barrier reefs. By doing so, early mistakes and difficulties can be avoided, saving precious time and finances, resources that can be redirected into the installation of new structures and obtaining scientific machinery that allow, for example, to accurately determine the species of picked corals or measure specific water properties. Coral Restoration Project Feridhoo's future includes the increase of nursery numbers, acquisition of advanced scientific tools, enhancing of already existing structures and, eventually, expansion to other islands of the Maldivian archipelago. All data and experience acquired from this study and presented in this paper could also be utilized as the foundation for new and diverse restoration programs.

3.5. Conclusions

Since its foundation in January 2022, Coral Restoration Program Feridhoo worked extensively to contribute to the enhancement of the nursery based coral restoration and to the safeguard and restoration of Feridhoo's barrier reef. The adoption of nurseries as the preferred recovering technique of choice allowed the researchers to start from solid ground based on numerous studies already performed on other areas of the world. Difficulties, obstacles and failures were encountered numerous times but the data provided by them was gladly collected with the intent to learn from the mistakes performed and refine on the methodologies used to increase the efficiency and efficacy of the project. Precious data was and is still being collected further expanding the applicative knowledge regarding the restoration of this small isle's reef. First small successes (transplantation of first 9 fragments back into the reef) were obtained bringing light to the optimistic view that the researchers involved share on the possibility to, one day, recover the incredible reef ecosystem that distinguish the Maldivian archipelago completely.

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