UNIVERSITY OF PADUA

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Health and morphology assessment of shallow coral reefs and artificial nurseries deployment in the western Maldives

Supervisor:
Prof. Marco Vincenzo Patruno

Co-supervisor:
Dr. Antonio Beggiato

Submitted by:
Castaman Caterina
n. 2002423

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Abstract

Corals are colonial organisms belonging to the phylum Cnidaria, presenting a wide range of different families and morphologies. Hard corals excrete calcium carbonate forming coral reefs, which are proper ecosystems fundamental for ecological functions and services. The Maldivian coral reef nowadays is threatened by anthropogenic issues, such as coral mining and destructive fishing methods, and natural phenomena including oceanic acidification and sea temperature increase. The increasingly high risk of losing this habitat requires the application of coral restoration methods aimed at assisting the damaged reefs. This study is divided into two main parts: the first one implies the evaluation of the health and composition of the shallow reef of Feridhoo (western Maldives) by means of transects and quadrats, including the analysis of the frequencies of different coral morphologies and presence of live, dead and bleached coral colonies and marine litter coverage. The analysis of the pictures taken of transect and quadrats via scuba and Peter diving was divided into three areas: north, east and south. The results showed the prevalence of ‘encrusting,’, ‘massive’ and ‘other’ coral morphotypes, with overall healthy colonies and a low bleaching rate. Marine litter was mainly found in the south, which was the area presenting the lowest live coral presence.

The second step involves the outline of nursery design and deployment for the long-term Coral Restoration Feridhoo Project. Four types of structures were studied, two fixed (cones and Feridhoo grid) and two floating (tree and rack). The nursery analysis was aimed at understanding their efficacy and differences in order to identify the most suitable method to apply in the near future. The description of the methods of cleaning and data collection is provided. Preliminary results on the data regarding the health and growth of the corals within the nurseries highlighted the higher overall mortality in the December and March checks and lowest coral mortality on the Feridhoo structure. Additionally, algal coverage was found to be the main cause of death and the main issue found in floating nurseries. Newly deployed fragments on the tree and rack frameworks displayed a high bleaching rate and fragment death due to the latter.

1. Introduction

1.1. Corals and coral reefs

Corals are animals that belong to the phylum Cnidaria, which also includes jellyfish and sea anemones (ICRI, 2021). Coral anatomy comprises singular units called polyps, which are small, tubular organisms encased in an exoskeleton of calcium carbonate called calicle. The upper end of the polyp 's body is composed by a mouth and tentacles, while the other contains a basal disc for substrate attachment (Thorp and Covich, 2001). A layer of tissue called the coenosarc lies beneath the polyps, facilitating nutrient sharing and the communication with one another (Chen et al., 2020). The ectoderm of the coral polyp is surrounded by nematocysts, typical cnidarian intracellular organelles that discharge venom for self-defence and predation when specific physiochemical stimuli are detected (Paruntu et al., 2022).

Corals are classified into soft and hard (or scleractinian); both kinds live in colonies. Soft corals are non-reef-building that grow wood-like cores and fleshy rinds for protection. On the contrary, hard corals create skeletons out of calcium (Oceaninfo, 2023) and could be classified into multiple morphotypes (**Fig.1**) depending on their branch and radial extension: 'arborescent,' 'caespitose/corymbose,' 'digitate', 'table-like', 'foliaceous', 'columnar', 'encrusting', 'solitary/free-living', and 'massive/brain-like'; each of these types has a specific growth-ratio and yield (Hughes et al, 2015).

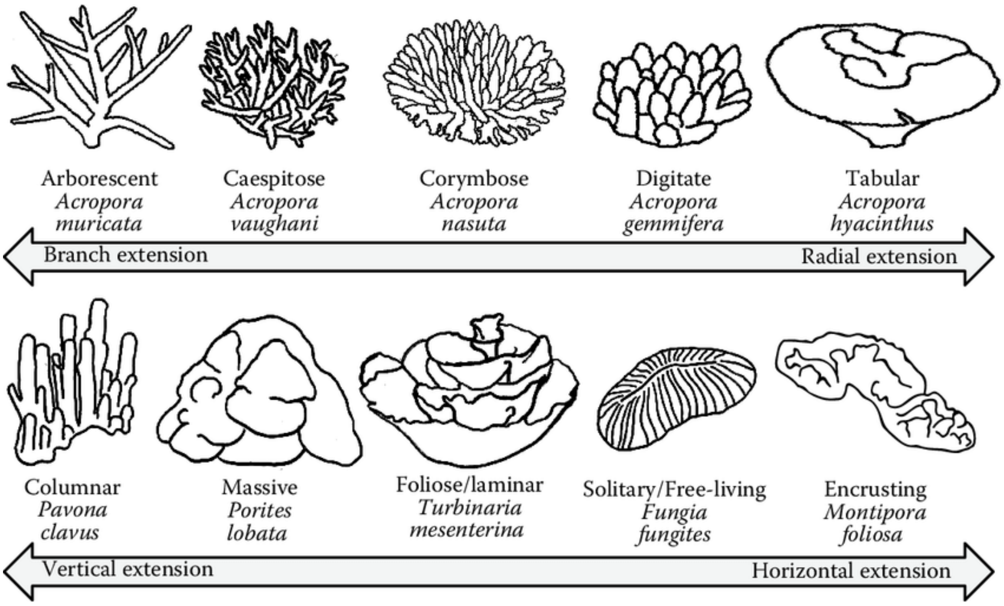


Fig.1: Morphotypes of Scleractinia corals represented according to their most prominent growth axis. (Pratchett et al., 2015)

Hard corals survive thanks to solar radiation and by gaining nutrients from the water through prey capture (NOAA, 2020). Nutrients needed by corals include both organic and inorganic compounds, naturally dissolved in seawater or introduced by human activities (D'Angelo and Wiedenmann, 2014) in various forms. During the late Triassic improved photosynthetic respiration, metabolism and growth rates, resulted thanks to the mutualistic coevolution with unicelled specific algal symbionts called zooxanthellae (Stanley and Swart, 1995). Zooxanthellae are photosynthetic unicellular dinoflagellate algae that live and photosynthesize inside corals' structure (Muscatine, 1980; Jackson, 1991), allowing them to survive and gain energy even in nutrient-poor environments (Muscatine and Porter, 1997). One of the factors conferring to corals their bright coloration is, in fact, zooxanthellae presence, as the algae contain yellow-brownish pigments that reflect and absorb light. The mutualistic relationship is based on the sustained physical contact between algae and host and on the bilateral movement of metabolites between them (Muscatine, 1980), which include O_2, CO_2, glucose, glycerol, and amino acids (US Department of Commerce, National Oceanic and Atmospheric Administration, 2019). The metabolites are used by the coral to produce proteins, fats, carbohydrates, and calcium carbonate. All hard corals present a relationship with symbionts, while soft corals lack it (Hughes, 1987; Mr. Van Arsdale, 2023).

Hard corals that build reefs are called hermatypic, while those that do not build reefs, such as soft corals, are called ahermatypic (Mr. Van Arsdale, 2023). Coral reefs are wave-resistant ecosystems composed of calcium carbonate deposits (Darwin, 1842) produced by hermatypic species that are typically found in tropical and subtropical regions of the planet (Odum and Odum, 1955; Connell, 1978). They are found in these areas because the optimal temperature tolerance range for most species is between 23 and 29 degrees Celsius (NOAA, 2023). Reef can be of three major types (**Fig.2**): fringing reefs consisting of corals attached to the volcanic borders, barrier reefs surrounding a volcano or a mountain, but not attached to it, and atolls that consist on oval or circular arrangements of coral reefs containing a central lagoon with multiple islands formed through time (Coral Reef Alliance, 2023). It's this last reef type that represents today's Maldivian ecosystem.

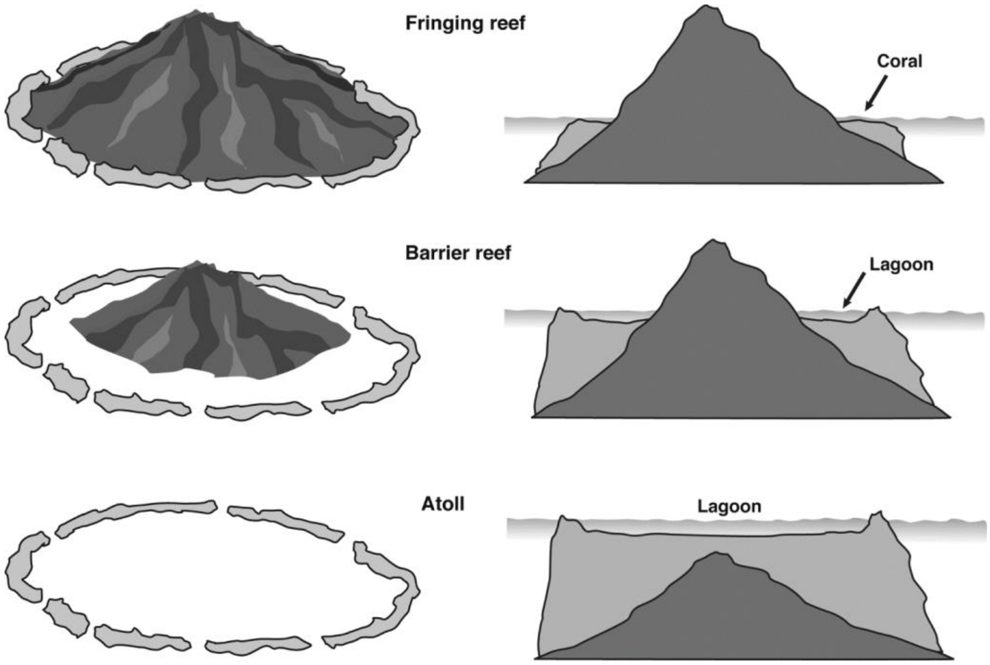


Fig.2: Graphical representation of the three types of coral reefs (Insights AS, 2023).

1.2. Importance of coral reefs and threats

Focusing on the environmental importance, coral reefs are estimated to house approximately 25% of all the marine life despite extending for less than 1% of the oceanic floor (Coral Reef Alliance, 2023). Around 500 million people worldwide depend directly on coral reefs for feeding, working and physical protection (Reef Resilience, 2023). Ecosystem functions consist on all the processes in the ecosystem that contribute to the self-persistence and provide advantages to the ecosystem itself, ecosystem services are all the benefits that ecosystem functions provide indirectly and directly to humans (Mumby et al., 2008). Monetary value through time was attributed to coral reef and related services, leading to a net worldwide economic value estimated to be nearly 10 billion of U.S. dollars per year (NOAA, 2023). Provisioning ecosystem services consists on the goods that humans gain from the ecosystem, in fact, corals contribute to the pelagic food web, increasing the productivity of local communities and supporting local fisheries (Sorokin, 1990; Grafeld et al, 2017). The marine aquarium fish trade entirely depends on coral reefs (Albert et al., 2015), as well as new medicines discovery and production (NOAA, 2023). Regulating services are related to benefits provided by the ecosystem natural processes. In this category a wide range of functions are included, since coral reefs are important spawning, nursery, breeding and feeding sites for the maintenance of a vast biological diversity and genetic library for future generations, thus increasing possibilities for the evolution of new species (Craik et al., 1990; Birkeland, 1997; Paulay, 1997). Cultural services are intangible benefits deriving from the ecosystem defining cultures, societies, beliefs, and experiences, the most important profitable service include recreational tourism for fishing, diving, and snorkelling activities, which represents the main source of income by increasing of over hundreds of million dollars local businesses (Dixon et al., 1993; Pendleton, 1995; Cesar, 1996). Supporting and habitat services consists on the sum of ecological functions that produce services by maintaining the habitat for the species (Woodhead et al., 2019). Coral reefs serve as a natural barrier, promoting their wave-breaking effect protecting the land (Moberg and Folke, 1999) and working as nitrogen fixers in nutrient-poor environments (Sorokin, 1993). Coral reefs also function as physical buffers against oceanic currents and provide the generation of sand substrate (Perry et al, 2015). The natural functions of coral reefs have a fundamental importance for human activities, since corals have the capability to detoxify and transform human wastes (Moberg and Folke, 1999).

Despite their fundamental role in tropical marine environments, coral reefs are among the most fragile ecosystems on the planet, endangered by numerous anthropogenic stressors and natural disturbances (Hoegh-Guldberg, 2010; Hughes et al., 2018; Leggat et al., 2019). Human-related destructive activities mainly include coral mining, consisting of coral removal from the reef for limestone and construction material extraction (Reefcause, 2021), destructive fishing methods (cyanide or dynamite fishing), fishing with small sized seine nets which can promote entanglement and coral rupture, uncontrolled tourism activities and oil extraction (Hawkins and Roberts, 1994; Johannes and Riepen, 1995; Dulvy et al., 1995). Different locations worldwide are threatened by diverse disturbances. Focusing on the Maldivian ecosystem, the main impacting factors include coastal development, land reclamation and beach replenishment on both local and resort islands. All the listed activities promote sediment dispersal (Zubair et al., 2011) which increases movement of fine particulates (Daby, 2003) intensifying water turbidity impacting the zooxanthellae photosynthesis rate.

Currently, natural disturbances impact coral reef ecosystems through multiple means, including oceanic acidification, consisting of a bidirectional cycle where accumulated carbon dioxide (CO_2) dissolved in sea water forms carbonic acid, that then releases one by one two atoms of hydrogen (H) becoming carbonate (CO_3) and vice versa. Since sea water pH is slightly alkaline (between 7.5-8.4), accumulation of CO_2 promotes pH decreas. This impacts the calcium carbonate ($CaCo_3$) supply of hermatypic corals (Gattuso and Hansson, 2011; Smithsonian Ocean, 2018) by inducing a reduction in the net calcification rate and skeletal density and by increasing coral porosity (Prada et al., 2017). Seawater acidity works together with seawater temperature increase. The rise in temperature is primarily caused by anthropogenic activity (McClanahan et al., 2007), provoking high stress levels in corals and leading to the well-known phenomenon of bleaching (Coles and Brown, 2003). Coral bleaching is a defence mechanism activated when the water temperature exceeds the optimal tolerance range of corals, and consists in the expulsion of zooxanthellae from polyps' tissue resulting in an increasingly white-ish discoloration (Brown, 1987; Goreau and Hayes, 1994). Bleaching does not directly imply corals death, as these organisms can survive the bleaching event, but they do tend to have significantly higher mortality rates compared to the healthy ones (NOAA, 2023).

1.3. Coral restoration and most applied techniques

Coral restoration is defined as "*the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed*" by supporting a reef, not creating a brand new one (Montano et al., 2022). Coral restoration is a discipline in continuous development, so new methodologies are always experimented. Among the techniques used worldwide, coral gardening is the most common, and it applies silviculture principles to the field of coral restoration, thereby minimizing damage to wild colonies (Rinkevich, 1995). The aim of coral gardening is the one of establishing self-sustaining systems on the long term, using artificial nursery structures to generate a stock of nubbins 'in situ' or 'ex situ.' Other experimental techniques include direct transplantation, which consists in the removal of live nubbins from an inhospitable degraded reef with consequent relocation in a new site where the coral has higher survival chances (Coral Digest, 2016). Additionally, larval rearing consists in the collection in designed spawn catching systems of coral eggs and sperm released during synchronous mass spawning to rear them in purpose-built enclosures followed by reef seeding (GBR Biology, 2022). Lately, new technologies even allowed the creation of artificial reefs through 3D printing: particular frameworks with textures and a design which mimics the suitable substrate needed by corals for larval settlement and growth (3DPrint.com, 2022). Rubble consolidation is another process aimed at restoring coral reefs by removing rubble accumulated because of natural high-magnitude disturbances, in order to re-expose the substrate underneath suitable for larval settlement (Ceccarelli et al., 2020).

1.4. Nurseries

Ex-situ artificial nurseries are usually located in land-based culture facilities to enable operators to monitor more easily coral growth but they need a constant water quality control (Barton et al., 2015; Montano et al., 2022). On the contrary, in-situ nurseries consist on temporary underwater structures deployed offshore and hosting coral fragments until they reach a size suitable for transplantation.

Before starting the project, the suitability of different sites must be assessed. A donor site, which is a location in proximity to the restoration site employed for nubbins collection, must be firstly identified. The selection of the donor site requires qualitative and quantitative preliminary investigations via snorkelling or SCUBA and must follow different criteria involving the distance from the nursery, the availability of live corals, the species biodiversity and the general environmental conditions (Montano et al., 2022). Once the donor site and coral species are selected, fragment collection is performed and no more than the 10% of the colony is removed (in order to minimize the risk of causing irreversible damages to the donor colony), with fragments being of a length near 8 centimetres (Frias-Torres and Montoya-Maya, 2019). The nursery site must be appropriate for coral gardening and is chosen after an accurate evaluation of the available areas. The artificial structures must present an adequate shelter providing protection from currents, waves, and wind action, as well as from anthropogenic harmful impacts. Furthermore, nursery framework can be fixed (anchored to the seabed) or floating (suspended in the water column) (Reef Resilience, 2023). The site must be of adequate depth for the species housed predominantly on a sandy substrate (the substrate is case-dependent, it may also be rocky or a mixture of rock and sand). The area must have low turbidity, low sedimentation, and adapted distance from the reef to avoid predation by corallivorous species but still near enough to allow ordinary maintenance procedures to be carried out efficiently and near to the donor and transplant site to minimize stress induced by transportation (Ogden-Fung et al., 2020; Montano et al., 2022). The selected restoration (or transplant) site, which consists of the proper intervention-requiring site, should be an area with calcium carbonate substrate dominance and with low rates of turbidity, sedimentation, hydro-dynamicity, and macro-algal presence. Furthermore, the factors that led to its degradation must have been eliminated or significantly reduced to maximize the success rate of the restoration (Reef Resilience Network, 2023).

The objectives of the following study comprise: (a) the evaluation of health and composition of the shallow reef by means of transects and quadrats; (b) the outlining of nursery design and deployment for a long-term coral restoration project, describing the methods of cleaning and data collection, and (c) the analysis of preliminary results regarding the health and growth rate of the corals within the nurseries to understand their efficacy in order to identify the most suitable method.

2. Materials and methods

2.1. Site/study area description

Feridhoo is a Maldivian island located on the western side of the Alif Alif atoll, approximately 87.96 kilometers west of Malè (4.05°N 72.72°E) (**Fig. 3**). The island is bordered by a shallow reef that extends until the atoll's margins. Beyond its boundaries, the reef's depth drops of 30 to 60 m (Atolls of Maldives, 2013) as a result of its location on the previously emerged volcano's borders. Feridhoo, as all the Maldivian islands, is characterized by a significant variation in environmental parameters due to the bi-annual reversal of monsoonal winds, which is mirrored by the water currents (Frontiers, 2021). As recorded in the Maldivian Meteorological Service database, two distinct seasons can be discerned: the wet season and the dry season. The first begins in mid-April and concludes at mid-December, and is characterized by a seasonal relative humidity fluctuating between 79-82%, from which it derives its name. During the wet season, the wind blows exclusively from west (Maldives Meteorological Service, 2023). The second, on the other hand, begins at mid-December and ends in mid-April, with a lower relative humidity oscillating between the 73-76%. Wind speed during this period is inferior than during the wet one and presents monthly oscillations: in January and February from the east while in April it begins blowing from the west, initiating the start of a new wet season (Maldives Meteorological Service, 2023). Moreover, the mean seawater temperature annually ranges between 28-31 degrees with lower peaks in December and January (28.2°C) and higher peaks in April (31°C) (Sea Temperature, 2023).

Fig. 3: Representation of the geographical position of Feridhoo in the Alif Alif atoll and the satellite picture of the island

2.2. Transects and quadrats

The analysis of shallow reef composition and health assessment was conducted between March and April 2023, within the region extending from the northern to the southern coast of Feridhoo, on its eastern side, adjacent to "BBQ Beach" (**Fig.6**). The decision to concentrate the effort specifically on this area was justified by the impracticality of working on the external western reef since its placement in oceanic proximity and its high exposition to strong currents made it too hazardous to undertake the operations without the boat support. The entire procedure was executed by a team of two divers. The equipment utilized included a 40 m long weighted rope, a quadrat measuring 50x50 cm (internally divided into nine equal smaller quadrats), a GoPro 7 Black camera, a PVC framework to roll up the rope, ordinary scuba gear and a Peter diving kit. For the first 30 m of the rope, a knot was tied at every 2 m interval and the quadrat was placed on alternate sides of each knot. A photograph was taken for every deployed quadrat. Subsequently, a 10 m gap was left empty on the rope to ensure the independence of each sample. The procedure involved the extension of the rope along the reef, at a depth ranging from 3 to 5 m. Each transect was positioned at the end of the previous one.

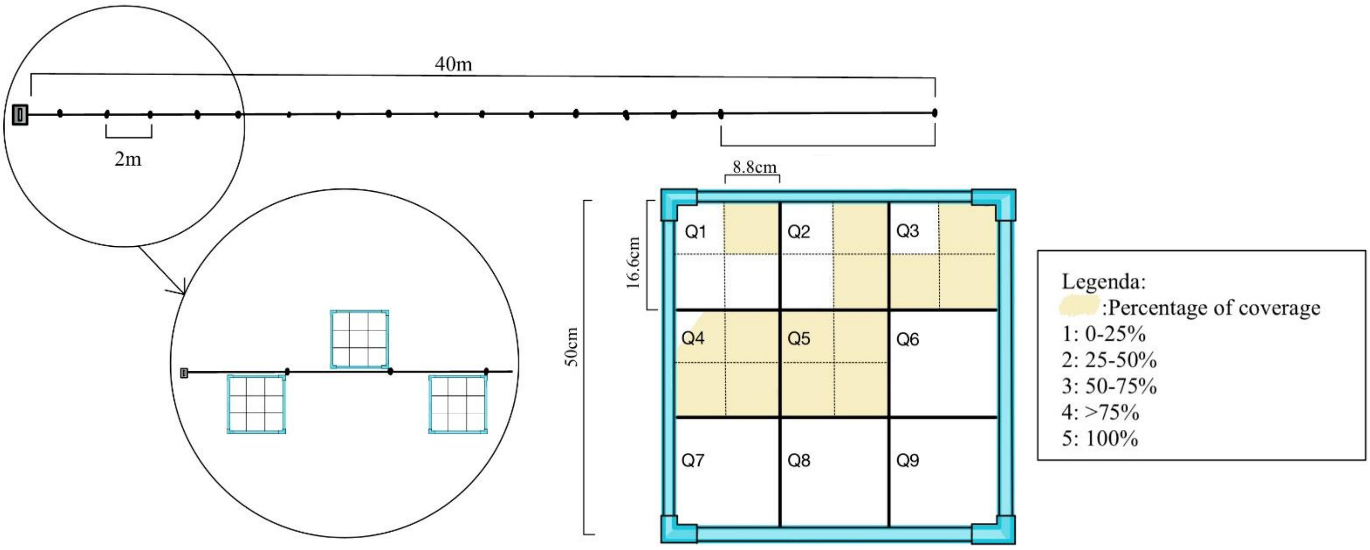


Fig. 4: schematic representation of the quadrat and transect structure

2.3. Nurseries design and deployment

To execute the Coral Restoration Project utilizing in situ nurseries, two types of structures were employed: fixed and floating, all placed in the 4.05°N and 72.72°E range. The fixed nurseries were made of iron and consisted in four cones and a grid. The floating structures were made of plastic and consisted in a tree and a rack (**Fig.6**). All the nurseries were deployed between mid-October 2022 and the beginning of December 2022. The cone structures were composed of four hexagonal frames connected by 30 cm long diagonal pieces, with the lower hexagon being larger (with a side of 60 cm) compared to the upper ones (**Fig. 5a**). To anchor the structure to the seabed, six additional 30 cm long diagonal pieces were added. The grid, which came in the shape of the word "Feridhoo," was long 300 cm horizontally, 100 cm wide and elevated of 100 cm from the seabed. The framework could contain a maximum of 60 fragments (**Fig. 5b**). All fixed nurseries were deployed at a depth of approximately 5 m and due to their stationery structure, nubbins attachment was permanent. As a result, the iron structures were expected to become a constituent of the coral reef composition. The lack of fragment removal deemed coral tagging negligible. For all fixed structures were used fragments belonging to the genus *Acropora spp*. and *Pocillopora spp*. To affix the nubbins, plastic cable ties were employed. Floating nurseries were suspended in the water column at a depth range between 7-11 m, kept stable by an anchoring system in contact with the seabed and, specifically for the tree nursery, a buoy in the apical pole. The tree nursery was sustained by supporting PVC poles forming a 195 cm long vertical trunk and 14 horizontal branches with a length of 50 cm (**Fig. 5c**). The vertical distance between one branch and the neighboring ones was 55cm. Coral fragments were tied to the branches with a transparent fishing nylon monofilament. The suspended coral was secured at one end by aluminum crimps, and the other end was knotted through the branch. Each branch had the capacity to hold up to 8 fragments, suspended in an alternating pattern, at 35 cm and 45 cm, away from the branch. Since the floating structures were temporary (corals were then transplanted into a suitable implant site), each fragment was tagged. Branches were labeled alphabetically from the lower one up to the "N" letter, while for single fragment identification numbers from 1 to 8 were defined, with the lower number always associated with the nubbin closest to the trunk pole. The rack nursery had a 400x200cm rectangular design manufactured in PVC containing internally 8 ropes, each one had 19 coral fragments tied with plastic cable ties (**Fig. 5d**). A 20 cm space was left between one rope and the neighboring one, as well as between one fragment and the other. Regarding the tagging procedure, each rope was labelled alphabetically up to the "H" letter and the fragment identification started from one side marked with a specific tape from number 1 going up to 19. The species housed in the tree nursery belonged to the family *Acropora spp*., while in the rack nubbins belonging to the *Pocilloporas pp*. family were affixed.

Structure maintenance was executed through cleaning procedure every two weeks and monthly measuring checks, which were performed utilizing ordinary scuba gear and Peter Diving equipment. The procedures were carried out by applying the same protocol regardless of the shape of the nursery implied. The cleaning equipment, kept inside a bag of adequate size, included metallic sponges, plastic brushes, spatulas, and protective gloves. The first step consisted of employing the metallic sponges and plastic brushes to remove the algal coverage in the empty space between one fragment and the neighboring one, then the spatula was utilized to remove barnacles and additional cirripeds. The measuring procedures were carried out employing a caliber, a whiteboard, and a pencil, all secured to the whiteboard with a piece of rope.

Dead fragments or nubbins showing signs of disease were promptly identified in the whiteboard, then removed to allow coral replacement to be performed to reach once again maximum structure capacity. *Acropora spp.* and *Pocillopora spp.* were the families selected with specific percentages determined based on the nurseries requiring replenishment. To collect fragments, the reef was searched for detached but still viable pieces; if none were found, pieces were obtained directly from the colony using bare hands, pliers or hammer and chisel, taking no more than 10% of the colony to ensure survival. Only live corals were considered as donors. The collected fragments were then broken into pieces approximately 8 cm in length utilizing pliers or hammer and chisel, with care taken to minimize the size of the resulting scar on the nubbin. Corals were kept in seawater inside a basket to minimize stress. To prepare nubbins for the tree nursery, aluminum crimps were attached to transparent fishing nylon monofilament employing the crimper. Once the fragments were measured for length using a caliber and the values were noted on the whiteboard, divers returned to each structure to bind the fragments to the empty spots.

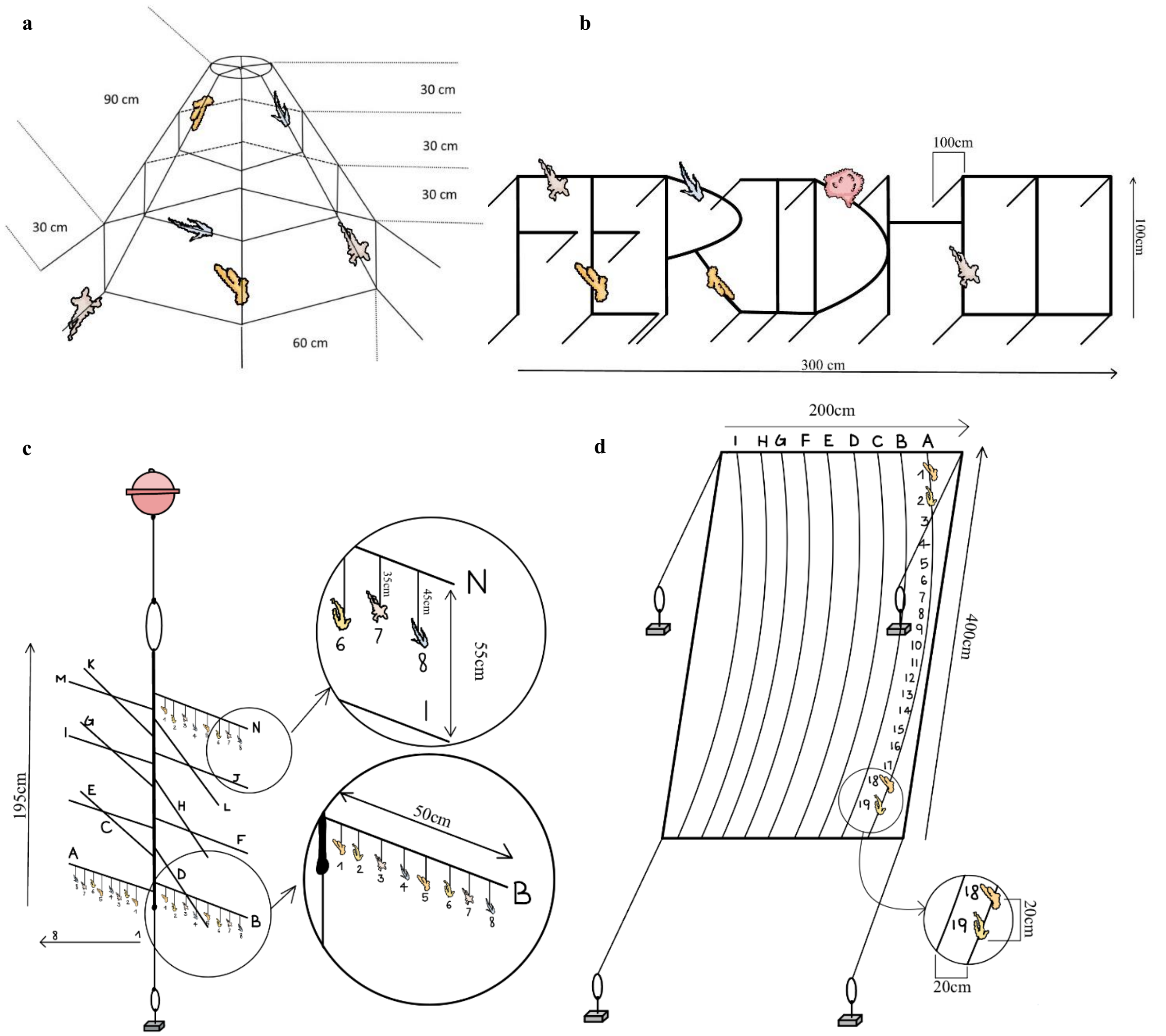


Fig. 5: graphical representation of the cone (**a**), the grid (**b**), the tree (**c**) and the rack (**d**) nursery.

2.4. Data collection and analysis

All the data obtained during transect procedures were collected on Excel (version 2302). The first factor examined was the recurrence of coral morphologies in the sample. When performing the sampling, the entire quadrat was used as the unit of focus. The categories of corals considered were: arborescent, caespitose/corymbose, table-like, foliose/laminar, encrusting, massive/brain-like, columnar, digitate, free-living, soft corals and others (with *Pocillopora spp*. included in the latter category). If in the picture analyzed a specific coral morphotype was present, but not completely included inside the frame, it was counted only if located on the right or upper side of the quadrat, otherwise it was ignored to avoid over-estimation. The means of the different transects were then grouped into areas (North, East, South) and analyzed as three groups for comparison. The second factor examined within each sub-quadrat unit considered the distribution of different substrates: live coral coverage, dead coral coverage, marine litter presence, bleaching extension, and other substrates presence (e.g., sand, rock, etc.). To each sub-unit a score from 0 to 5 was attributed, where 0 indicated to the absence of the parameter considered, 1 represented a coverage between 0-25%, 2 between 25-50%, 3 between 50-75%, 4 a coverage in the 75-99% range and 5 represented the complete distribution throughout the area (**Fig. 4**). The score was estimated for all the 9 sub-units and the average value for each quadrat was calculated and inserted into the dataset. For the graphical representation the 15 quadrats composing each transect were grouped together and only the mean value for the entire transect was considered and included in the division into areas as macro categories.

For what concerns the nurseries, data collected differed among fixed and floating structures, since just in the latter coral tagging was performed and length recorded. Because the number of pieces returned to the maximum after each replacement, there was a constant predicted number of beginning corals for each fixed structure at each monthly inspection. The following characteristics were recorded in fixed nurseries: external temperature at check time, total number of fragments (from which the quantity of lost corals was estimated), number of dead, healthy, and unhealthy corals. Furthermore, the occurrence of algae covering, bleaching, or illness signs was reported among the sick tallied. In floating nurseries, the following data were gathered for each tagged fragment: external temperature at check time, overall health state (where 1 equal alive, 2 equals dead, and 3 indicates illness presence), and length at the closest mm to compute the growth rate. Additionally, concerning algal coverage and bleaching, to each nubbin was assigned a score ranging from 0 to 5, with 0 indicating complete absence of its distribution, 1 a value in the 0-25% range, 2 between 25-50%, 3 between 50-75%, 4 in the 75-99% range and 5 indicating complete spread along the fragment. All subsequent computations in the statistical analysis consider the corals present on floating nurseries from the first deployment date (23rd and 27th of November 2022 for the tree, 12th December for the rack) and not the replacing ones to avoid value underestimation.

All the statistical analysis and graphical representation were carried out on R version 4.2.2. employing R packges “ggplot2” and “MASS”. Anova tests were applied to study the mortality in all the nurseries and the coral growth rate in the floating ones. Furthermore, a two-sample t-test was performed to study the critical issues of newly deployed fragments on floating nurseries.

3. Results

3.1. Transects and quadrats data

The study examined a total of 20 transects (**Fig. 6**), eight of which situated in both the northern and southern zones and four in the eastern one, resulting in a total sampled area of 75m^2.

The coral morphology study comprised 11 distinct morphotypes in the sample (**Fig. 7a**). According to the data analysis, 'encrusting' corals were the most common morphotype in all the three zones (25.2% in the north, 30.8% in the east, and 36% in the south).

Observing the northern region, although 'caespitose/corymbose' colonies were far fewer than 'encrusting' corals, they were nevertheless the second most common morphology (with a distribution rate of 21.4%), followed by 'massive/brain-like' (15.4%). The fourth most prevalent group was 'other', with a distribution of 12%. Furthermore, 'arborescent' corals were found to be distributed for the 9.4% while in the case of 'tabular' corals diffusion was equal to 7.7%. Only in the northern area the distribution rate of 'digitate' corals and 'soft' was found to be equal, with 3.6% for each. 'Free-living' corals (0.86%), followed by columnar (0.51%) and foliose/laminar (0.17%), were the least observed morphotypes.

Focusing on the eastern area, the 'corymbose' morphotype was the second most prevalent accounting for 24% of diffusion. The east site was found to be the only one having the distribution of 'massive' corals equal to that of the 'other' category (9.5% each). There also happened to be an equal proportion of 'digitate' and 'tabular' corals (7.3% per type). The 'arborescent' morphotype occurred in 6% of the examined area, whereas soft corals accounted for the 4%. The 'free-living' (0.75%) category, subsequently followed by the 'columnar' and the 'foliose' (0.37% each) corals, were the least abundant morphotypes observed in the eastern area.

Concerning the southern region, the 'other' coral morphology was the second most prevalent (20.18%), followed by the 'massive/brain-like' (19.5%) and, finally, the 'corymbose' (9.4%). 'Soft' corals were discovered to occupy 5.7% of the tested site, whereas 'tabular' morphology occupied 4%, outnumbering 'digitate' corals (3%). The 'arborescent' (2%) and 'columnar' (0.2%) typologies were the least abundant. The southern section was discovered to be the only one devoid of 'foliose' and 'free-living' colonies.

a

b

Area	Substrate type	Percentage
N	Arborescent	9.41
	Caesorymbose	21.39
	Digitate	3.59
	Table-like	7.70
	Columnar	0.51
	Massive/brain like	15.40
	Foliaceous/laminar	0.17
	Solitary/free living	0.86
	Soft	3.59
	Encrusting	25.15
	Others	12.15
E	Arborescent	6.23
	Caesorymbose	23.81
	Digitate	7.33
	Table-like	7.33
	Columnar	0.37
	Massive/brain like	9.52
	Foliaceous/laminar	0.37
	Solitary/free living	0.75
	Soft	4.03
	Encrusting	30.77
	Others	9.52
S	Arborescent	1.97
	Caesorymbose	9.43
	Digitate	3.07
	Table-like	3.95
	Columnar	0.22
	Massive/brain like	19.52
	Foliaceous/laminar	0.00
	Solitary/free living	0.00
	Soft	5.70
	Encrusting	35.96
	Others	20.18

c

Area	Coverage type	Percentage
N	live mean	23.56
	dead mean	32.00
	marine litter mean	1.17
	bleaching mean	0.95
E	live mean	20.90
	dead mean	29.52
	marine litter mean	1.52
	bleaching mean	1.16
S	live mean	15.76
	dead mean	16.78
	marine litter mean	5.24
	bleaching mean	0.74

Fig. 6: Transects position is revealed, along with their numerical order and subdivision per area (**a**). Summary tables of data collected for coral morphologies (**b**) and substrates coverage (**c**) are presented.

The distribution of the evaluated coverages was unequal (**Fig. 7b**). Among the coverages evaluated, coral was the most widespread throughout all three spots tested. A generalized coral distribution was predominantly observed in the north (55.6% of the total coverage) and east (50.4%) compared to the southern zones (32.5%). Interestingly, 'dead coral' substrates, accounted for 26% of the total 75m^2 examined and exhibited a significantly greater prevalence than 'live coral' substrates (20%). The northern location reported the largest percentage of dead corals (32%), subsequently followed by the eastern site (29.5%) and the southern site (16.8%). A similar pattern was observed in terms of live coral coverage, with the majority found in the north (23.5%), compared to the east (20.9%) and south (15.8%). It was determined that 'marine litter' was far more prevalent in the southern region (5.2%), with a value nearly twice as high as the total of the other two zones (1.16% in the east and 1.51% in the south). Fabric, plastic, and metal were among the ‘marine litter’ components identified on the reef. The substrate types discussed accounted for 51% of the overall 75m^2 coverage, with the remaining 49% made up of ‘bare rock’, ‘sand’, and ‘other substrates’. The abundance of ‘bare rock’ and ‘sand’ was found to be higher than that of the ‘other substrates’ since the latter was only included once inside a quadrat and was used to indicate the iron framework of the grid nursery. Although bleaching was the least observed event since it was missing in most observations, it had comparable percentages in all three sites (approximately 1% north, 1.2% in the east, and 0.7% in the south).

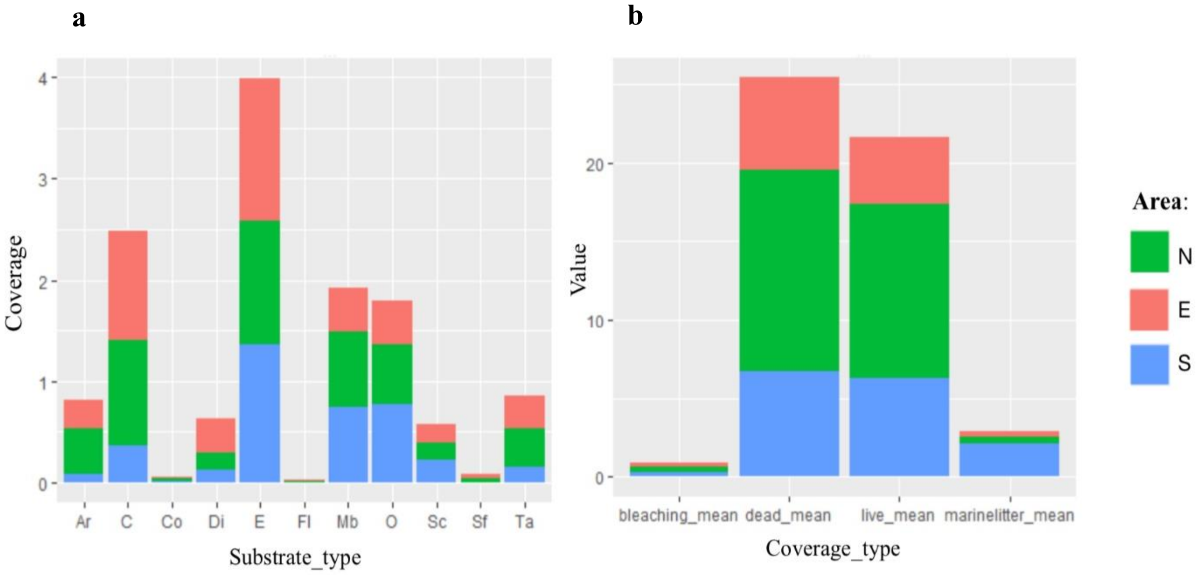


Fig. 7: Histogram representing the distribution of the relative frequencies of coral morphotypes, where’ Ar’ means ‘arborescent’, ‘C’ means ‘corymbose’, ‘Co’ indicates ‘columnar’ corals, ‘E’ indicates ‘encrusting’, ‘Fl’ means ‘foliose/laminar’, ‘Mb’ represents ‘massive/brain-like’ morphotypes, ‘O’ represents the ‘other’ category, ‘Sc’ denotes the ‘soft coral’ category, ‘Sf’ the ‘solitary/free-living’ one and ‘Ta’ the ‘table-like’(**a**). Histogram portraying the substrate coverage along the sampled transects (**b**), where ‘bleaching_ mean’ indicated the diffusion of bleaching in the different areas, ‘dead_mean’ and ‘live_mean’ both refer to coral substrate coverage depending on their health condition and ‘marinelitter_coverage’ denotes the diffusion of marine litter in the sampled locations.

3.2. Nurseries

Cone A, D and the grid had a maximum capacity of 60 corals, while cones B and C could accommodate up to 50 fragments The total number of nubbins in the floating nurseries was 112 for the tree and 152 for the rack.

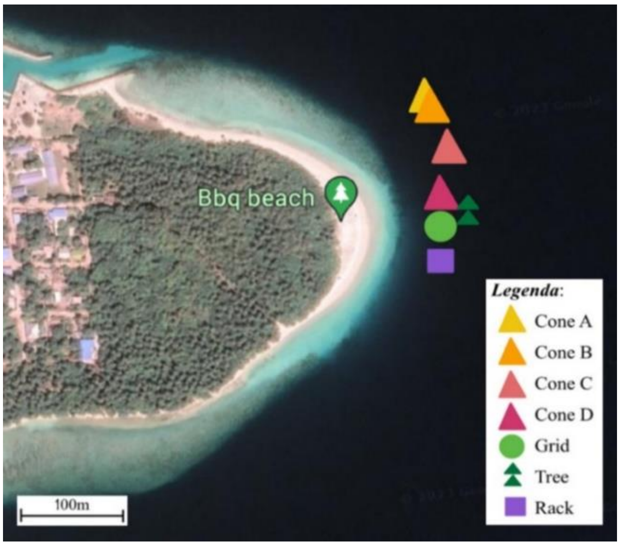
The first ANOVA, which focused on the fragments' mortality rate, found significant differences between the months (or checks) and the mortality rate, as well as between the latter and the nurseries. A statistically significant relationship between the month of March and the mortality was revealed, with a greater rate than predicted. Furthermore, December check revealed the highest significant mortality rate compared to all the other months. A significant difference between the Feridhoo nursery and the death rate was then discovered, implying that the grid nursery had much lower mortality levels than the other structures.

In terms of the monthly growth rate in the floating nurseries, a statistical difference was found in relation to the check, while nothing remarkable was observed related to the two structures. More specifically, the most relevant difference in growth was observed between January and April, as fragments grew significantly different in these two months in both nurseries. The lowest growth rate was found in January (averaging 0.41 cm in the tree and 0.34 cm in the rack), while the greatest was reported in April (averaging 0.87 cm in the tree and 0.77 in the rack).

Statistical significance was found in the tree and rack for the algal diffusion, however there was no significant difference between the two nurseries when considering bleaching and diseases. To further explore the distribution of algae, a thorough analysis was conducted, and the findings (**Fig. 9a**) revealed a dominant predominance of algae at level 1. A comparable frequency of level 1 algal coverage was detected in both structures (56% of total sampled fragments). However, there was more algal diffusion in the tree at levels 2 (7.5%) and 4 (2%), compared to the rack (5.6% at level 2 and 1.5% at level 4). Additionally, level 3 algal coverage was exclusively observed in the tree (2%), and no diffusion at level 5 was noted on either structure. The principal cause of death in floating nurseries was found to be algae (**Fig. 9b**) with a greater incidence in the tree framework. Bleaching and fragment loss were found to be more prevalent in the rack, whereas diseases were exclusively observed in the tree.

Upon examination of the newly deployed fragments on the floating nurseries, it was observed that critical issues related to algae and bleaching varied significantly depending on the structure to which the nubbins were attached to. The ANOVA showed that there was a significant difference between the two nurseries in terms of these issues. Remarkably, all newly deployed fragments in the tree nursery showed no signs of these problems. The rack structure, on the other hand, exhibited a high incidence of complications. Out of 19 newly deployed fragments, 6 died, with 50% of them dying due to algae and the other 50% due to bleaching. It is worth noting that out of the 6 fragments that did not survive, 2 of them perished in March while the other 4 died in April. Moreover, among the 13 corals that survived, 9 displayed criticisms. The problematics of the unhealthy survivors were related to bleaching for the 89%, while the remaining 11% were affected by algae. Focusing on the time, it was clearly visible that all corals displaying bleaching were deployed in March 2023.

a



b

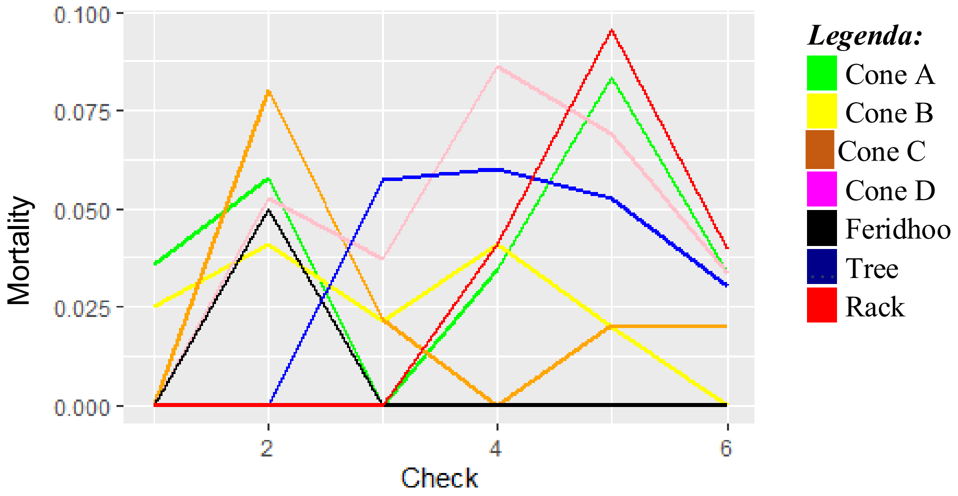


Fig. 8: Graphic representation of nurseries location (**a**) and graph representing the mortality rate in relation to the check (**b**). The latter includes in the checks where 1 means November, 2 indicates December, 3 represents January, 4 means February, 5 stands for March and 6 represents April.

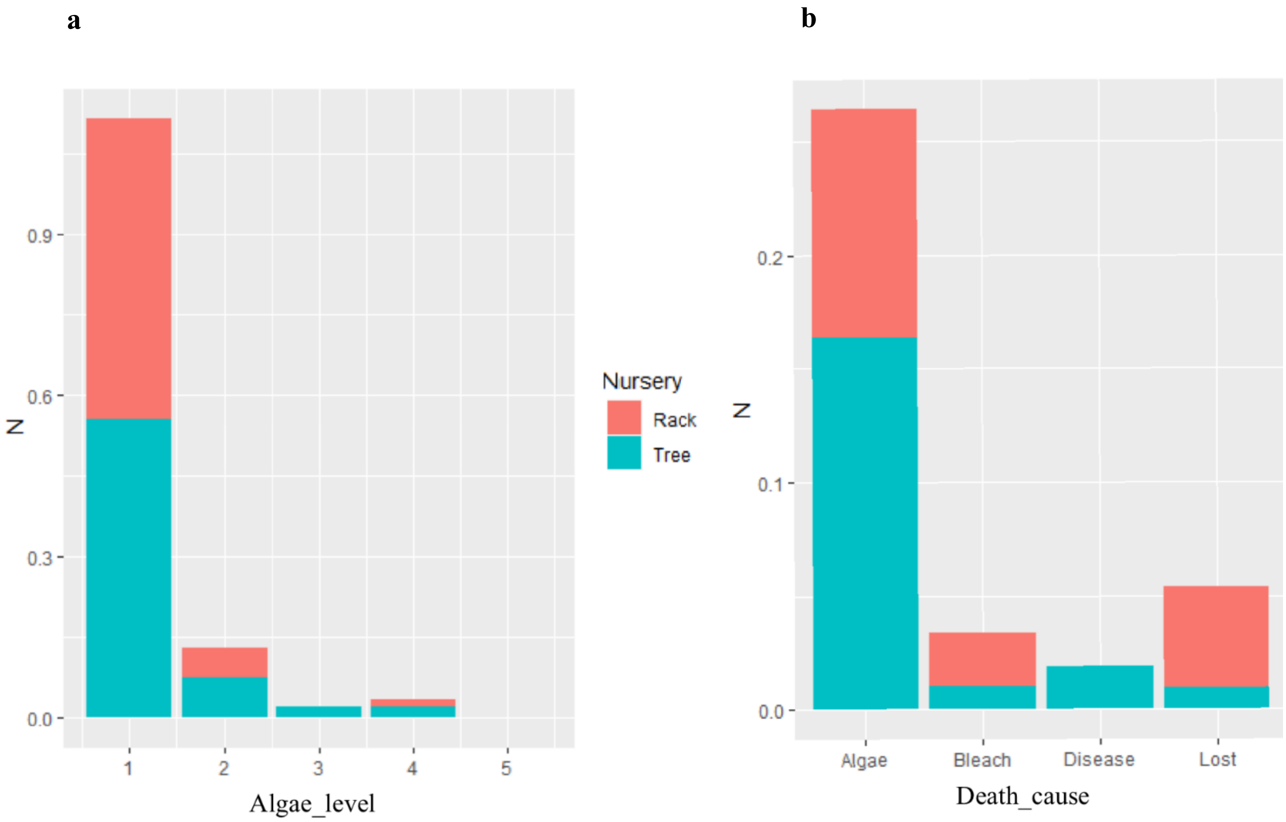


Fig 9: Histograms representing the relative frequencies of each level of algal coverage (**a**) and the relative frequency of each cause of death in the floating nurseries (**b**).

4. Discussion

4.1. Transects and quadrats

Focusing on the coral morphotypes in the sample (**Fig. 7a** 'Results'), a huge difference in the distribution of 'encrusting' and 'corymbose' morphotypes was observed. This discrepancy emerged because the 'encrusting' morphotype was more frequently counted due to smaller size and more disseminated nature, leading them to be more likely to be captured inside the quadrat. The 'corymbose' morphotype tended to form larger colonies that were less likely to be counted within the quadrat, even if they extended only minimally beyond its boundaries. Notably, since the 'arborescent' and 'table-like' morphotypes form tended to constitute wider colonies, a higher difference in the result was observed. On the other hand, considering distribution of 'arborescent,' 'massive' and the 'other' (consisting for the wider percentage of colonies of *Pocillopora spp.*) categories, their abundance depended on the susceptibility of the coral type to fluctuation in the environmental parameters. In fact, 'arborescent' corals (mainly belonging to the *Acropora spp.* family) were the least present, probably because among the three morphotypes they are the most susceptible to bleaching and death when changes in water parameters are verified (Pisapia et al, 2019). The bleaching events of 1998 (Tkachenko, 2014) and 2016 (Pisapia et al, 2019) have impacted, among all coral families, the distribution of *Acropora spp.* Prior to these events, the most distributed coral morphologies in the shallow reef were, in fact, the 'arborescent' (including 'tabular' and 'corymbose'), followed by the massive one (Pisapia et al., 2016). After these events the mortality of Acropora spp. reached values up to 80% in specific Maldivian islands (Blaschke, 2010; Marine Research Centre, 2016), meaning that the minor presence of Acropora spp. compared to 'massive' and 'encrusting' may be related to the fact that these corals still need some time to recover from the past temperature-related mortality (Fallati et al., 2020). *Pocillopora spp.* corals were more present than the latter due to their higher resistance to environmental changes, but not as much as the 'massive' ones. No bleaching was observed on *Pocillopora spp.* or 'massive' colonies. Moreover, 'massive' corals were found to be more prevalent than the ones classified as 'others', probably because they are less affected by the external environment due to their higher resilience to increased temperatures (Pisapia et al, 2019). This study provides a further example of the inverse relationship among the morphotype's growth rate and its susceptibility to rising water temperatures (Morgan and Kench, 2012). In fact, 'arborescent,' 'corymbose' and 'tabular' corals, which were the ones displaying the higher growth rates due to their more complex form, were also the ones displaying bleaching, as opposed to 'massive' corals (characterized by a lower growth rate due to their continuous surfaces). It is also fundamental to mention that the procedure implied was performed at a depth between 3 and 5 m, but considering that in the Ari and neighboring atolls there is an evident zonation in coral reef composition dependent on depth (Nepote et al., 2016), it is assumable that at different depths there might be different abundances of the investigated morphotypes. Oceanic reefs in the Maldives are dominated by ‘massive’ corals (Bianchi et al., 2016) because more exposed to natural disturbances such as waves and currents. In shallower reefs, the distribution of ‘arborescent’, ‘corymbose’ and ‘tabular’ morphotypes belonging to the *Acropora spp.* genus (Done, 1982; Madin and Connolly, 2006; Lasagna et al., 2010a) may decrease through time (Erftemeijer et al., 2012), depending on the high exposure to waves and currents of their non-trauma-resistant structure. The studies performed in the Maldivian archipelago show a resemblance with the data exposed in this study (Montefalcone et al., 2020; Fallati et al., 2020; Nepote et al., 2016), but the majority is focused on periods of time related to the bleaching events of 1998 and 2016, and on shallower reefs (because new methods developed can be applied at low depths). For this reason, further investigations must be done, preferably at higher depths (more than 6 meters) and in the same years.

Concerning the substrates (**Fig. 7b** ‘Results’), the three zones displayed different coral distributions, with a consistent pattern in which the north and east areas had a larger prevalence of both dead and living corals, while the south had much lower values. This occurrence might be explained by the fact that there were several quadrats with 100% coverage by dead coral, while in quadrats presenting live coral colonies frequently existed a spot with a limited quantity of missing or dead coral substrate in the regions with 'arborescent,' 'corymbose,' and 'tabular' colonies. This might be because these morphotypes were more vulnerable to breaking due to human disturbances such as boats, marine trash deposition, or scuba diver movement. The southern zone also presented a much higher prevalence of marine litter compared to the other locations. Since scleractinian corals are prone to bind to accessible surfaces and produce calcium carbonate, the tissue debris was the only one with freshly formed hard coral colonies (*Acropora spp*. and *Pocilloporas spp*.), although in small numbers and only on the upper surface. It might not be incidental that the area with the most marine litter was also the one presenting the lower number of corals, since macroplastics cause a great variety of damages (Nama et al., 2023) on the coral reef promoting coral death, and may have provided a wide coverture that did not allow the observation of the substrate underneath. The low coral presence in the southern area may be dependent on the seabed type, in fact, the zones with a high prevalence of sand are the ones where less corals are found. This is due to the marine larvae behavior, which are influenced by a wide range of physical cues (Levenstein et al., 2022). Different studies have demonstrated that coral larvae prefer to settle in locations presenting surface features or roughness that maximizes the contact between the coral larva and the area (Callow et al., 2002; Scardino et al., 2006). Sand substrates do not provide the appropriate attachment features, rendering coral recruitment unsuccessful, and as consequence the area results in a location with low-coral presence. Sand-prevalent areas tend to be the most turbid ones, and turbidity decreases the water quality reducing the available depth and light of the photic zone, leading to a smaller zone available for larval settlement (Jones et al., 2015). Furthermore, a failure in larval settlement may lead to a subsequent detachment deteriorating water quality increasing turbidity and affecting the remaining larvae (Gilmour, 1999; Nozawa and Okubo, 2011). The extensive presence of marine litter in the southern location may be also related to the morphology of Feridhoo, since the proximity with the island's open landfill (positioned in the south of the island) may have increased the build-up of debris since part of it may arrive by land instead of only by sea. Moreover, the sampling was carried out during the dry season, period characterized by the marine current flowing from east/north-east towards west/south-west. As a result, because of the spear shaped morphology of Feridhoo, the current gets divided into two fluxes. The first one, less intense and on the northern side, and the second, the strongest, flowing on the southern side of the island. Consequently, more debris accumulate in the south, increasing the chance of entanglement in the reef. An additional sampling conducted in the wet season could provide further explanations concerning this issue. The bleaching phenomenon was observed with a very low frequency, mainly because on each colony ('arborescent,' 'caespitose/corymbose' or 'tabular') presenting bleaching the coverage was at level 1, while in the cases in which a whole coral was bleached, its dimension was always found to be minimal leading to an overall low bleaching rate. A sampling in April and the following months, respectively from the period where the bleaching threshold is reached (NOAA, 2023) to the months that do not present danger, may be recommended, in order to check whether the phenomenon may have increased in its frequency in the weeks following the sampling (for further information, see **Fig. 1** in 'Supplementary Materials' chapter).

4.2. Nurseries

Concerning the significantly higher mortality rate in December, the explanation could be based on the higher stress experienced by fragments. Since December was the first check performed on all the nurseries, the higher mortality might be linked to the stress corals undergo when removed from the colony and attached to the structure, needing a stronger effort to adapt, thrive and survive in the new conditions (Herlan and Lirman, 2008). In March a higher mortality of nubbins was also observed, probably because in that time of the year temperatures begin to rise (NOAA, 2023), adding further stress to the fragments (see **Fig. 1** in 'Supplementary Materials'). One of the most important findings regards the increasingly lower mortality rate on the Feridhoo nursery, suggesting a higher level of efficiency compared to the other structures. The grid structure may have displayed a low mortality rate because of the attachment of fragments on the same plane, which might have mitigated sediment accumulation (Nature Seychelles, 2018) while providing the nubbins with an equally distributed light regime. Nursery site reveals to be a negligible variable, since cone D and the grid gave different results concerning mortality even if they were in neighboring positions. A higher rate of general success in the fixed nurseries was then observable compared to the floating ones. This might be related to the higher capability of the iron to accumulate dirt more slowly than the PVC. It must be noted that multiple families of corals were attached on fixed nurseries, while only specific families were deployed on the tree (*Acropora spp*.) and rack (*Pocilloporas spp*.). The different results may for this reason be related to the species-specific characteristics of corals, implying that the confrontation among the two floating nurseries must be focused on other parameters.

The fragment growth on both the tree and rack increased with time, resulting in the largest size difference between the January and April checks. The growth rate was low in January, perhaps because newly deployed nubbins needed time to adapt to the nurseries, while in April it was high possibly because of the more elevated temperatures that promoted calcification (Crabbe and James, 2008).

Algal diffusion was the primary cause of fragment death in floating nurseries because corals and algae compete for light, (Miller, 1998; McCook, 1999), with one competitor's performance decreasing as the other's grows. Benthic algae may overshadow coral surfaces (Theobald, 2003) but cannot induce fragment mortality until they are dispersed throughout the entire coral surface. In other cases, if a coral dies, algae can easily colonize and grow on its surface without representing the actual cause of death (Hughes, 1989; McCook et al., 2001). Only experimental evidence can provide information to define in each case if algae are the factor leading to fragment death or a direct consequence of it. Furthermore, the bigger is the colony, the more difficult is for algae to outgrow colonizing it (McCook et al., 2001). Fragments size varies in the range between 7-14 cm, making it easier for algae to colonize them compared to bigger reef colonies.

In this study, a large number of fragments showed algal presence almost entirely at level 1 (so not disperse enough to cause nubbin death) (**Fig.9a**), meaning that algae were present and diffused on a large number of fragments but had a minimal impact on them. This may be due to reduction in the number of herbivores directly feeding on algae (McCook et al., 2001). Floating nurseries, in fact, were deployed at a reasonable distance from the reef so that herbivorous fish could not easily reach their location. The position was also chosen because the seabed was leveled instead of sloped, sand was the main substrate so that there was no chance for the bottom weight of damaging the reef. The distance from the reef was functional also to impede to corallivorous fish to reach them. Additionally, algal incidence may depend on seasonal temperature fluctuations, since changes in temperature affect the algal photosynthetic and metabolic activity (Fulton et al. 2014). Since algal diffusion may also depend on nurseries maintenance, an additional cleaning routine performed each month can provide clues on the relationship between the frequency of the cleaning procedures and algal diffusion on the structures, whilst further checks during the wet season may provide additional data of the correlation between algal diffusion and water temperature.

The newly deployed fragments on the tree and rack nurseries performed differently. Since no critical issues were highlighted on the tree, it could be stated that either the structure was more suitable for promoting a successful attachment of each new fragment, or the *Acropora spp.* genus had a lower susceptibility to develop health issues compared to *Pocillopora spp*. The first hypothesis may be more accurate, since *Acropora spp.* and *Pocillopora spp*. are both characterized by a high susceptibility to thermal stress (Guest et al. 2012). Focusing on the rack, all new nubbins deployed in March displayed a high mortality rate due to bleaching or, if survived, a bleaching rate at level higher than 2. Since in no other checks a so strong outcome was observed, it could be hypothesized a relationship between the bleaching and the check. This is further supported by the fact that March is the month in which water temperatures begin to rise (NOAA, 2023), resulting in an increased thermal stress (**Fig. 1** in the 'Supplementary Materials'). Also in this case, since *Acropora spp.* and *Pocillopora spp*. do not differ in terms of sensitivity to thermal stress (Guest et al. 2012), the focus should be shifted on the effectiveness of the rack nursery.

5. Conclusions

The study provides fundamental information on the health and composition of the shallow reef around Feridhoo island by means of transects and quadrats. Furthermore, the preliminary results on coral survival and growth within the artificial nurseries allowed to understand the efficacy of the “Coral Restoration Project Feridhoo” and helped in the identification of the most suitable structure. Based on this study, it can be concluded that the Feridhoo reef is primarily composed by ‘encrusting’ corals, which clearly showed to have the most widespread distribution. Additionally, there was a significant presence of ‘caespitose/corymbose’ corals, primarily due to their fast growth rate and ability to withstand disturbances. In the southern area, there was a noticeable lack of coral and a significant presence of sandy substrate, with visible marine litter coverage. A potential correlation between the abundance of microplastics and the low coral coverage in this area could be hypothesized. On the contrary, the study observed a wider coral coverage in the northern and easter areas, although predominantly consisting of dead corals. The widespread mortality might be attributed to both anthropogenic and natural disruptive factors. Notably, all three areas exhibited minimal coral bleaching rates.

For what concern artificial nurseries the study highlighted the significance of December and March as the months presenting higher mortality rates. The stress caused to corals in December, during their first deployment on the nurseries could explain the higher registered mortality. New and quicker fragmentation and transplantation methods should be investigated. Moreover, the seawater temperature increase occurred during the month of March is likely to have induced a significant thermal stress to corals with a subsequent peak in mortality. Among all the artificial nurseries, the “Feridhoo” fixed framework exhibited the highest suitability level for coral survival. This may be attributed to the arrangement of nubbins on the same plane, providing an optimal light regime and minimizing sediment movement. The primary cause of death on nurseries was determined to be algal coverage. Algae act by overshadowing coral surfaces and thus impeding zooxanthellae photosynthesis. Algal growth was found to have a widespread distribution, but at low frequencies and this could be attributed to the nursery’s location, management practices, and seasonal variations in seawater parameters.

In conclusion, the study in general demonstrates that the Feridhoo reef is predominantly healthy although displaying evidences of anthropic impact. In the near future a further employment of fixed nurseries built similarly to the Feridhoo framework might represent an efficient method to promote coral restocking in the areas where corals struggle to survive or are completely missing.

6. Supplementary materials

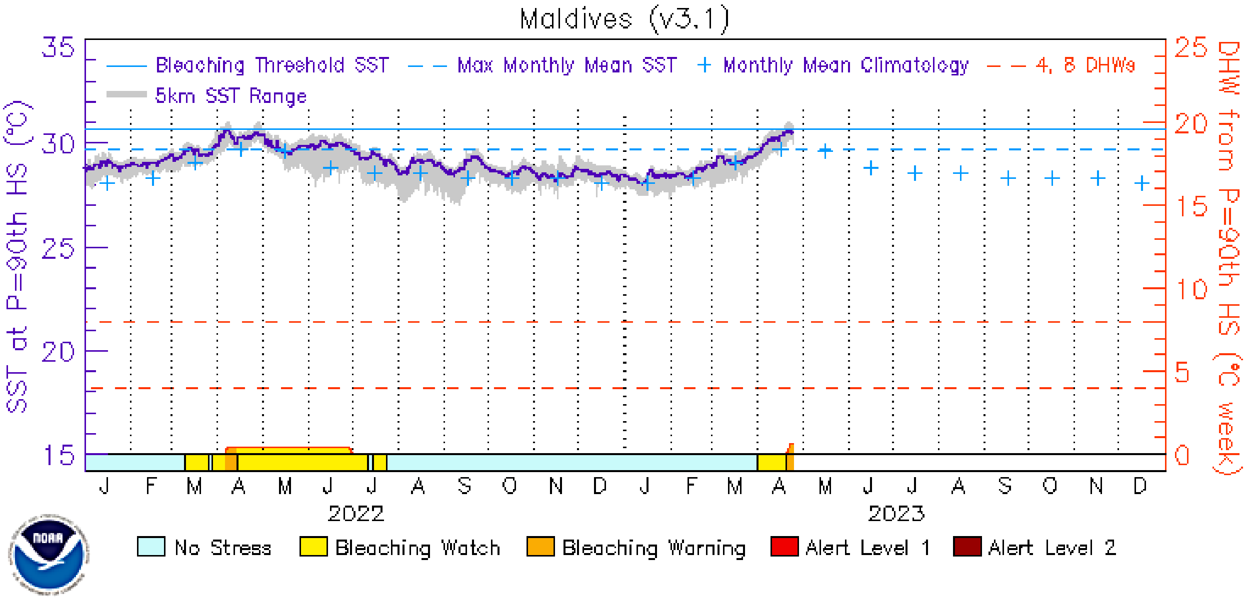


Fig. 1: comprehensive summary of current satellite-monitored bleaching thermal stress conditions in Maldives in 2022-2023 (NOAA,2023).

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