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Optimizing Coral Farming: A Comparative Analysis of Nursery Designs for *Acropora aspera*, *Acropora muricata*, and *Montipora digitata* in Anantara Lagoon, Maldives

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Abstract Maldivian coral reefs have undergone a substantial degradation due to a combination of anthropogenic pressure and global climate change. In response to the 2016 coral bleaching event, Anantara Dhigu, Anantara Veli, and Naladhu Private Island launched the Holistic Approach to Reef Protection (HARP) project, aiming to restore the house-reef. This study, a key component of HARP, evaluates the effectiveness of two coral nursery designs, rope-based and metal table-based, at two depths (~2 m and~5 m) for the propagation of *Acropora aspera*, *Acropora muricata*, and *Montipora digitata*. Over six months, bimonthly underwater surveys assessed growth rates, ecological volume, health conditions, disease presence, predation, and survival rates. Results indicate that rope-based nurseries generally outperform metal tables, with higher growth rates and better survival rates observed on ropes. Specifically, *Montipora digitata* showed the most substantial growth at 2 meters depth, reaching up to 5 cm in six months. Additionally, rope nurseries demonstrated significantly lower predation rates and better overall health conditions compared to metal tables. While coral survival was comparable across nursery designs, the study suggests that shallower depths favor coral growth due to enhanced light availability. However, shallower depths also correlated with higher mortality during a recent bleaching event, emphasizing the need to balance depth considerations with potential thermal stress. This study underscores the advantages of rope-based nurseries in promoting coral growth and survival, offering valuable insights for coral restoration strategies in shallow lagoon ecosystems.

Keywords Coral; Coral nursery; Coral reef; Restoration strategies; Rope nurseries

1 Introduction

Coral reefs represent one of Earth's richest ecosystems in terms of biodiversity, offering invaluable goods and services estimated to be worth up to $9.9 trillion annually (Costanza et al., 2014). Nearly 1 billion people reside within 100 kilometers of a coral reef, highlighting a global-scale societal reliance that places at the same time a substantial stress on reef health (Burdett et al., 2024). Anthropogenic activities and climate change-induced stressors, such as increase in ocean temperatures, acidification, deoxygenation, pollution and sea level rise, pose profound challenges to the resilience and survival of coral reefs in many countries. Among the regions significantly impacted is the Maldives, where coral reefs have experienced substantial degradation due to a combination of local human pressures and global environmental changes (Hughes et al., 2017; Pancrazi et al., 2023). Maldivian coral reefs experienced three severe recorded bleaching events in 1998, in 2016 and in 2024. After the 1998 bleaching event, more than 90% of hard corals have reported to died (Edwards et al., 2001), and it took 16 years for reefs to recover the pre-bleaching values of live hard coral cover (Morri et al., 2015). Following the coral bleaching event of 2016, a pilot program named the Holistic Approach to Reef Protection (HARP) was initiated by Anantara Dhigu, Anantara Veli, and Naladhu Private Island, to preserve and restore the coral reef, in collaboration with Coral Reef CPR. The project was funded through Dollars for Deeds, a Corporate Social Responsibility initiative implemented by Minor Hotels. The latest bleaching event occurred in 2024. Coral recovery and mortality studies are currently ongoing. In response to these challenges, numerous coral conservation initiatives are being implemented across the Maldives, particularly within island resorts and community islands (Dehnert et al., 2022; Pancrazi et al., 2023). These efforts aim to rehabilitate and sustainably manage shallow coral reefs, crucial for supporting biodiversity, fisheries, and coastal protection (Cinner et al., 2018).

The current study constitutes a pivotal component of the ongoing HARP project, focusing on evaluating the efficacy of different coral nursery designs in facilitating the growth and survival of coral fragments at varying depths (~2 m and ~5 m). Both coral nursery designs are low-cost, adaptable-scale and can be used by both island resorts and community islands. Rope-based and metal table-based nurseries were employed to cultivate coral fragments of *Acropora aspera*, *Acropora muricata*, and *Montipora digitata* sourced from naturally broken colonies within the same location as the nurseries. Fragments from the same colony were evenly distributed between the rope and metal frames for consistency. Bimonthly underwater surveys were conducted over a period of six months to analyze the following parameters: (i) growth, (ii) ecological volume, (iii) health condition, (iv) presence of disease, (v) predation, and (vi) survival rate.

Rope nurseries outperformed metal tables in terms of coral survival and overall performance. The absence of predation on ropes significantly enhances survival rates for *A. aspera* and *A. muricata*, making rope nurseries a more effective technique for propagating corals in Maldives' lagoons.

2 Results and Analysis

Growth rates after 6 months monitoring (Figure 1), *A. aspera* exhibited a similar growth rate in rope-based and table-based nurseries at ~2 meters with no statistically significant difference (Figure 1a). At ~5 meters, the growth rate was significantly higher in table-based nurseries compared to rope-based nurseries (P< 0.001). Similar results were reported for *A. muricata* (Figure 1b), with a higher growth rate on table-based nurseries at ~5 meters compared to the rope- based nurseries. No significant differences were found at ~2 meters. For *M. digitata*, the growth rate was significantly higher for corals on rope-based nurseries at ~2 meters compared to ~5 meters and to table-based nurseries (Figure 1c, P< 0.001).

The highest growth was recorded for *M. digitata* at ~2 m on ropes-based nurseries, reaching 4.48 ± 2.04 cm, followed by *A. aspera* and *A. muricata*, with 2.21± 0.76 cm and 2.06± 0.89 cm, respectively. High growth rates were also reported on metal-tables based nurseries at ~5 meters, where the growth rate for all species exceeded ~3 cm over six months. The ecological volume for the different species is reported (Figure 2).

The ecological volume was overall higher at ~2 meters compared to ~5 meters for all the analyzed species (Figure 2a, 2b, 2c), reflecting more favorable conditions for coral growth in shallower depths. No significant differences were found in the bimonthly surveys between rope-based nurseries and table-based nurseries (Figure 2). However, the analysis of EV variation after 6 months shows statistically significant variations (Figure 3).

For *A. aspera* the variation in EV was statistically higher on ropes at ~2 meters, compared to ropes at ~5 meters (Figure 3a, * P<0.05). No significant differences were found for table-based nurseries. For *A. muricata*, the variation in EV was not significant influenced by nursery design and/or depth (Figure 3b). *M. digitata* (Figure 3c) showed a significantly higher EV variation on both ropes (**** P<0.0001) and tables (** P<0.01) at 2 meters, increasing from 2699.6 ± 233.2 to 5808.6 ± 512.8, respectively. No significant differences were found in at 5 meters (Figure 3c).

The general health of the coral fragments (Figure 4), Ropes at both ~2 and ~5 meters had the best health conditions, with only less than 20% of coral fragments showing partially unhealthy colonies (Figure 4a, 4b, 4e, 4f, 4i, 4j). Rope-based nurseries reported no predation over the study period of 6 months. Table-based nurseries presented predation on both *A. aspera* and *A. muricata* due to *Drupelia* spp, especially at ~2 meters. No other predator’s species or bite marks were recoded (Figure 4c, 4d, 4g, 4h, 4k, 4l).

The survival rate was overall lower in coral grown on tables-based nurseries compared to the rope-based nurseries, for all 3 species. Interestingly, *M. digitata* displayed the highest survival rate, 80~90% in all the experimental conditions. No statistically significant differences due to depth or nursery design were reported (Chi-square P=0.7192, Fisher's exact test, P=0.7623, n=15, Figure 4).

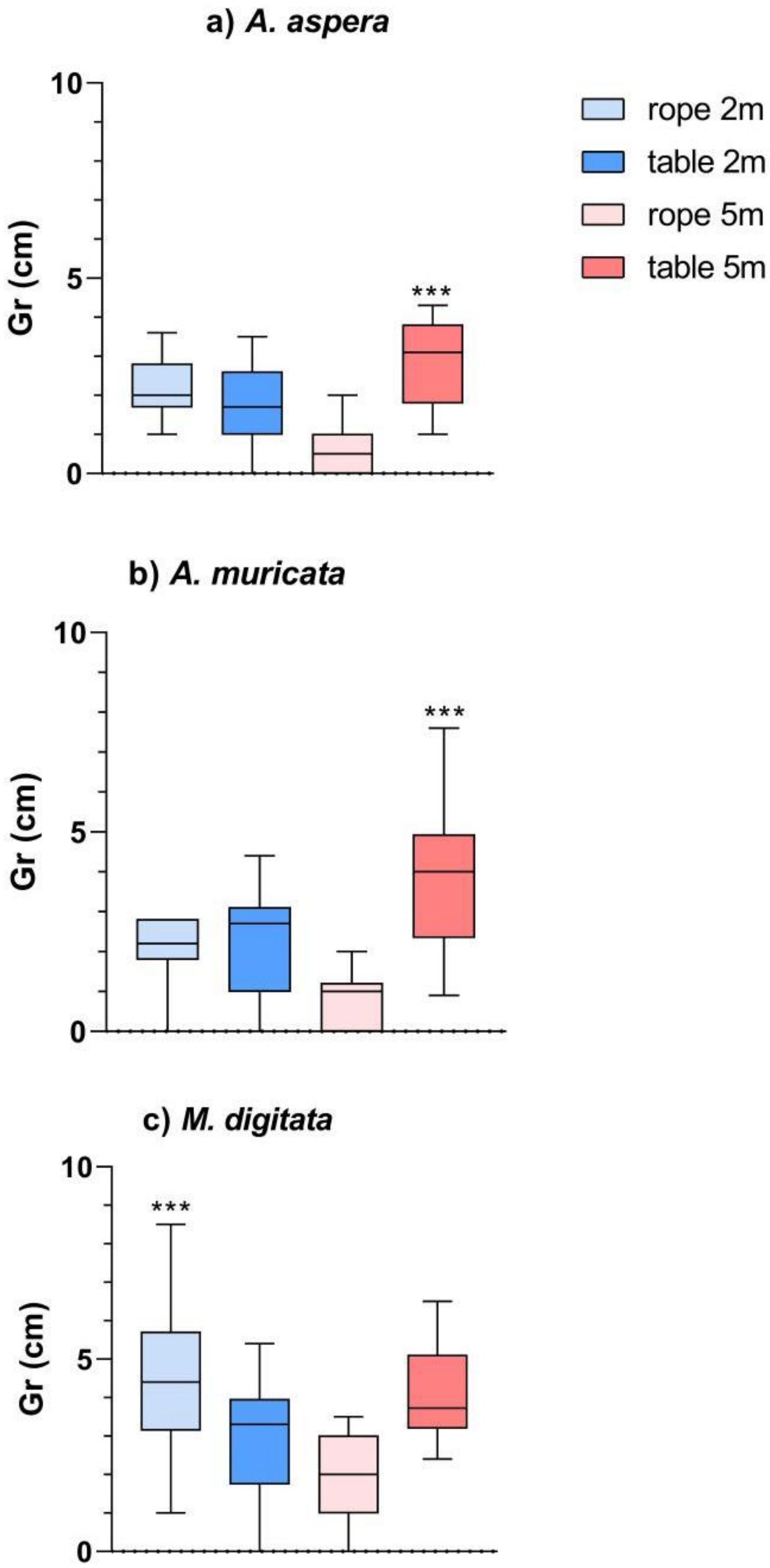

Figure 1 Coral growth after 6 months of monitoring, (a) *A. aspera*, (b) *A. muricata* and (c) *M. digitata* colonies at ~2 and ~5 m, grown on rope-based nurseries and metal-table based nurseries in Anantara Lagoon, Maldives. ***P<0.001. One-way ANOVA, Tukey's post test (P<0.05), N=15.

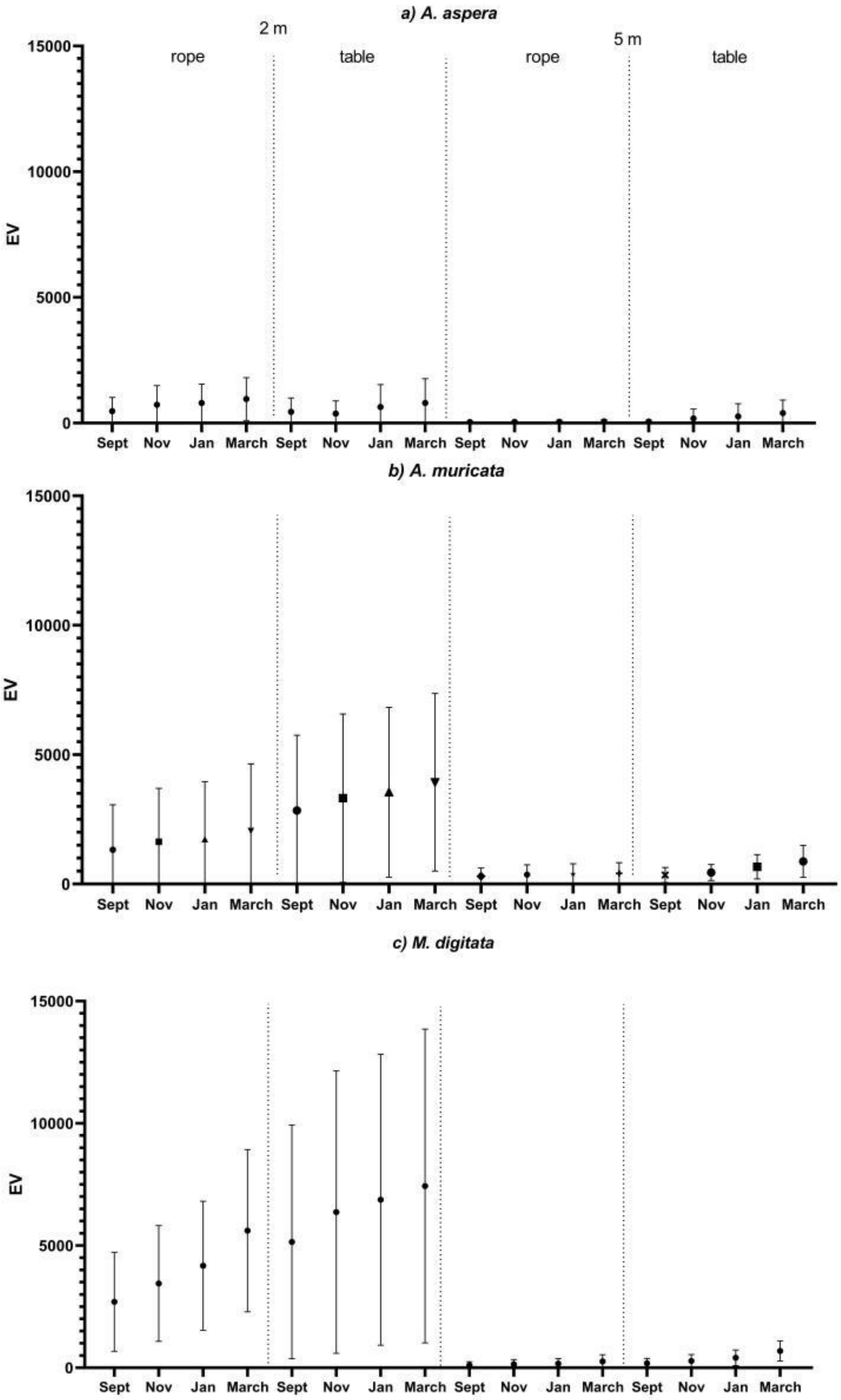

Figure 2 Bimonthly Ecological Volume (EV) measurements for *A. aspera* (a), *A. muricata* (b) and *M. digitata* (c) colonies grown at ~2 and ~5 meters, on rope nurseries and metal table nurseries from September to March 2024. One-way ANOVA, Tukey's post test ($P<0.05$). N = 15

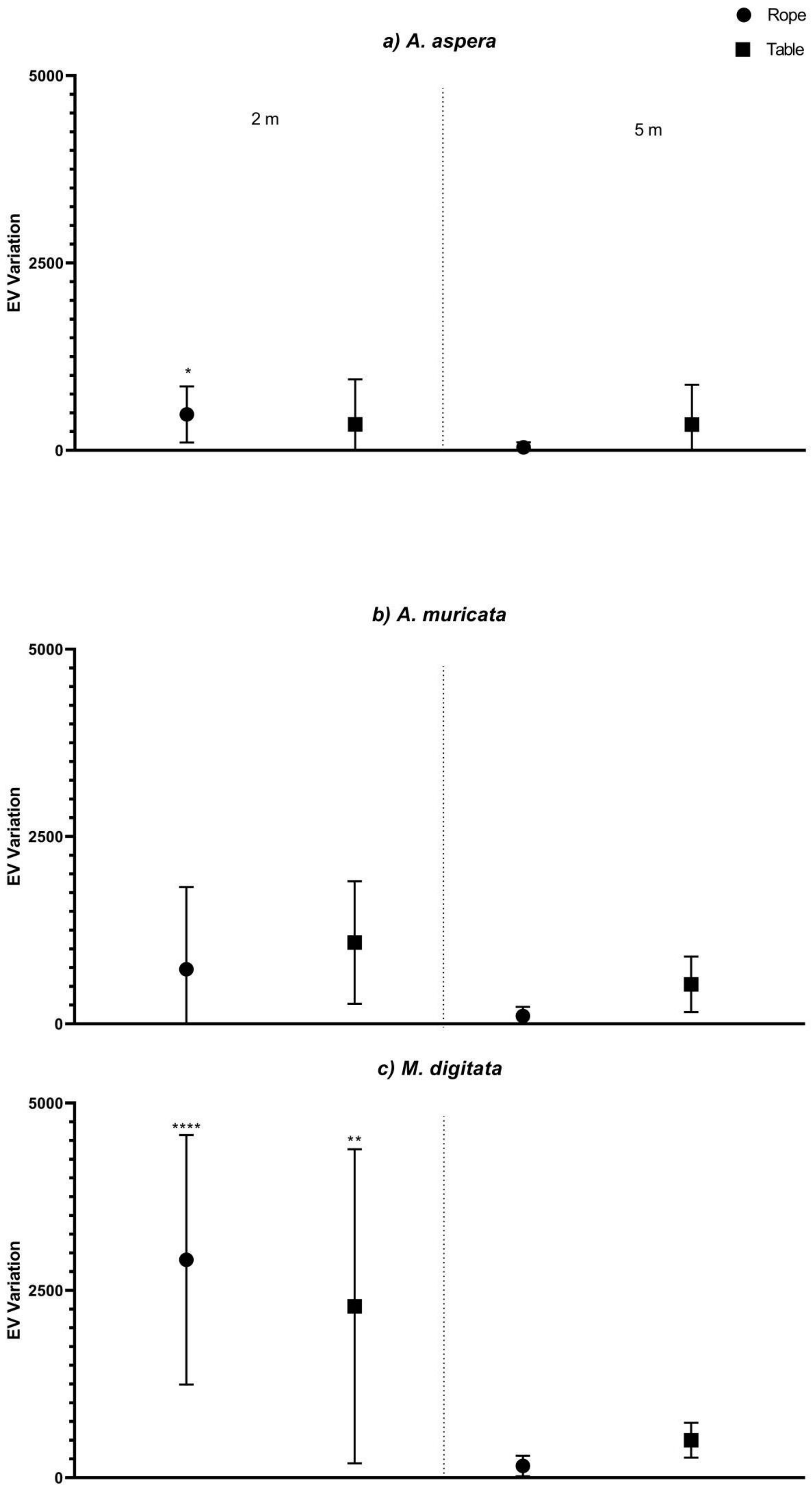

Figure 3 EV variation after 6 months in *A. aspera* (a), *A. muricata* (b) and *M. digitata* (c) colonies grown on rope-based nurseries and metal table-based nurseries at ~2 and ~5 m depth. ****P<0.0001, ***P<0.001, **P<0.01, *P<0.05. One-way ANOVA, Tukey's post test (P<0.05). N = 15

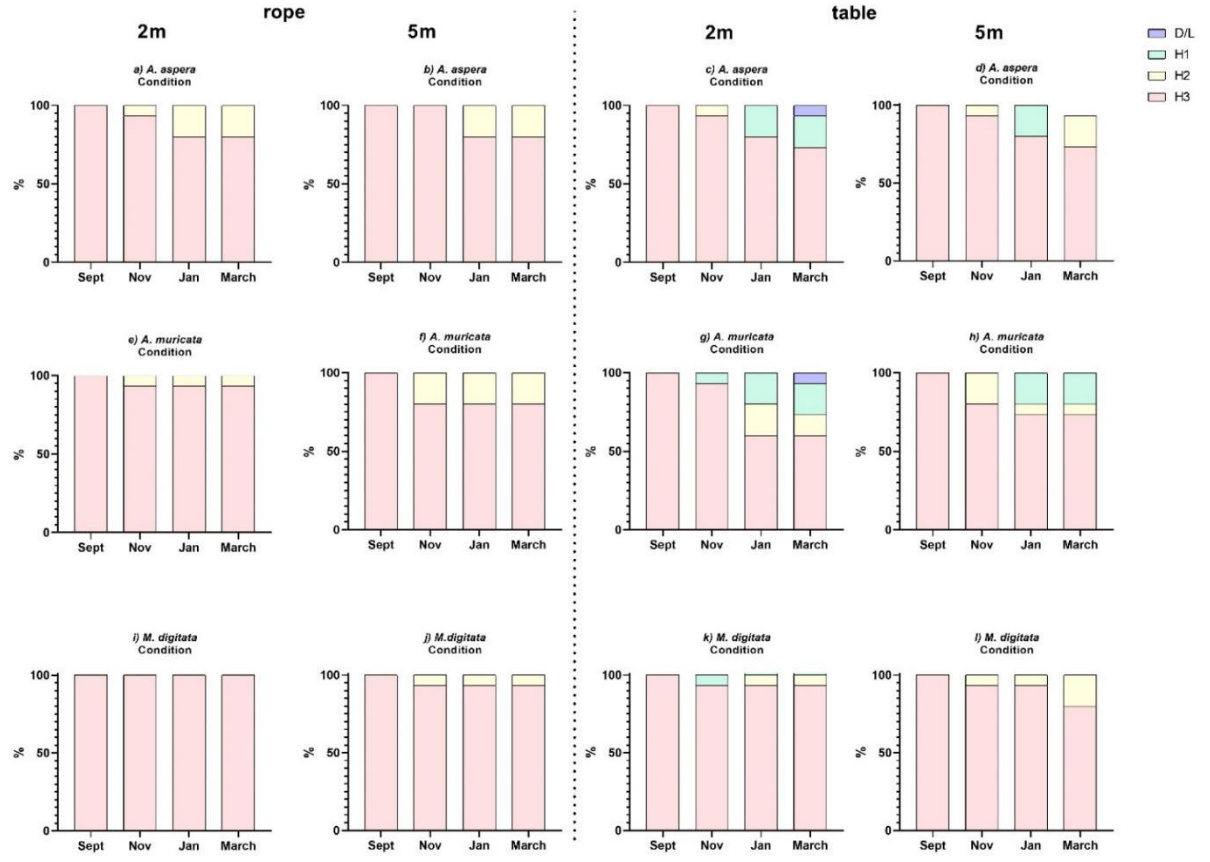

Figure 4 Condition of *A. aspera*, *A. muricata* and *M. digitata* colonies (n = 15 per depth) in different nurseries design, at ~2 and ~5 m, at T0 (September) and in November, January and March 2024 (6 months in total). D/L, dead or lost, H1- less than 50% living tissue on the fragment, H2- more than 50% living coral tissue, H3- fragments with 100% living tissue. One-way ANOVA, Tukey's post hoc test ($P<0.05$). Chi-square and Fisher's exact test ($P< 0.05$). N = 15

3 Discussion

Our study offers valuable insights into the impact of nursery design and depth on coral growth and overall health, with implications for coral restoration practices in shallow lagoons.

The higher coral growth at ~2 m observed in this study confirms that shallower depths provide better conditions for coral growth due to increased light availability and higher temperatures, which are critical for photosynthesis and coral metabolism (Kahng et al., 2011; Hughes et al., 2018). The lack of significant differences in growth rates between rope-based and table-based nurseries at each depth suggests that the design of the nursery may not be as critical as the depth in influencing growth rates, as previously reported by Edmunds and Elahi (2007). Environmental factors like light and water quality may play a more substantial role in coral growth than the specific nursery design used.

The higher ecological volume reported for rope-based nurseries suggests that the rope design might contribute to a more beneficial microhabitat for this species, as supported by previous research demonstrating that ecological volume can be influenced by both the depth and the structural complexity of the nursery (Baker and Vize, 2015; Rogers et al., 2020). It is possible that the increased space available on ropes compared to table-based nurseries facilitates better coral growth. Despite this, coral health remained unaffected by depth or nursery design suggesting that corals can maintain good health if environmental conditions remain within tolerable ranges (Hughes et al., 2012). A key finding of our study was the absence of predation in rope-based nurseries. This study confirmed that nursery design can influence the level of predation, with structures like ropes offering fewer opportunities for predators to access coral fragments (Rogers and Miller, 2020). The absence of bite marks and predator species other than *Drupelia spp*. is probably due to the choice of the experimental area, distant approximately 678 meters from the house reef, displaying a lower coralivorous species abundance. Survival rates for *Acropora aspera*, *Acropora muricata*, and *Montipora digitata* were approximately 86%, 80%, and 90%, respectively, after 6 months, with higher mortality observed in the initial 2~4 months followed by stabilization. The results suggest that while survival rates were not significantly affected by nursery design or depth, the initial period is critical for coral establishment and survival.

During the recent bleaching event we observed that shallower depths, such as ~ 2 meters, were associated with higher mortality rates. Specifically, Anantara's nursery at ~2 meters experienced a 50% mortality rate (except for *Montipora digitata*), whereas corals grown at ~5 meters had only a 20% mortality rate (personal observation). While shallower depths generally promote faster growth and higher survival rates under normal conditions (Kuffner and Toth, 2012), they also expose corals to greater temperature fluctuations during heat stress events (McClanahan et al., 2004; Hughes et al., 2012). This highlights the importance of selecting nursery depths with consideration for potential thermal anomalies and/or bleaching events.

Rope-based nurseries, as demonstrated in our study, offer notable advantages including reduced predation and increased ecological volume. They reduce predation rates and contribute to a more favorable microhabitat for coral fragments (Rogers and Miller, 2020). An additional advantage of rope nurseries is their mobility. This characteristic is increasingly important in the context of risings sea temperature and frequent bleaching events. The ability to relocate entire ropes or, on a larger scale, entire nurseries, to different depths or areas allow for adaptive management strategies, potentially improving coral survival rates during thermal stress events. By integrating a comprehensive bleaching monitoring program, managers can optimize the placement of rope-based nurseries to mitigate the impacts of bleaching and other environmental stressors. From an economic perspective, the initial setup costs for rope-based nurseries are generally lower compared to metal table designs, making them a cost-effective option for initial implementation (Edmunds and Elahi, 2007). In terms of maintenance, rope nurseries require relatively minimal upkeep. Regular maintenance primarily involves cleaning the ropes to remove algae, competing invertebrates and fouling organisms and periodically lifting the ropes as coral colonies grow and increase in weight. These tasks are less demanding compared to the extensive maintenance often required for metal table designs, which can suffer from issues like rusting and structural degradation (Baker and Vize, 2015). The metal staples used in the rope-based nurseries, typically last between 8~10 years before needing replacement, reflecting their durability (personal observation).

Outplanting from rope-based nurseries is also straightforward. Once the coral colonies have reached maturity, they can be outplanted individually using several methods such as epoxy, cement, or nails. Alternatively, entire ropes can be relocated and outplanted together. In such cases, the rope is secured to the substrate using natural materials or additional nails, facilitating the establishment of the coral colonies in their new environment (Harrison and Wallace, 2012). This flexibility in outplanting methods adds to the practicality of rope-based nurseries, making them a versatile tool for coral restoration.

Despite the challenges, large-scale coral restoration using rope-based nurseries has the potential to deliver substantial ecological and economic benefits. Healthy coral reefs support vital ecosystem services, including fisheries, tourism, and coastal protection. The economic feasibility of these nurseries is supported by their contributions to reef health and the associated benefits to local economies. Demonstrating the effectiveness of these nurseries through pilot projects and securing funding from governmental, non-governmental, and private sectors will be critical for scaling up and sustaining these efforts.

This study also considered the use of *Montipora digitata*, a species known for its high growth rates and greater resistance to environmental stress compared to other Acroporidae species. *Montipora digitata* is particularly suitable for restoration projects due to its robust nature and rapid colonization capabilities (Gomez et al., 2011). This species has been reported to withstand varying environmental conditions better than more sensitive species like *Acropora spp*. (Veron, 2000; Harrison and Wallace, 2012). The use of *M. digitata* in the coral nursery could provide several advantages including faster growth rates (Mumby and Harborne, 2010) and high resilience to temperature stress (Meroz-Fine et al., 2016) and bleaching event (personal observation).

4 Materials and Methods

4.1 Study area

The study was conducted in Anantara Dhigu Lagoon, located on a reef system on the eastern rim of South Malé Atoll, GPS coordinates: 3.973047, 73.500734 (Permit number PA/CN-CR/2023/05).

The site is characterized by a heavily modified reef system encompassing natural and reclaimed islands (Figure 5). The nearest protected area, Guraidhoo Kanduolhi, is approximately 9 km southwest.

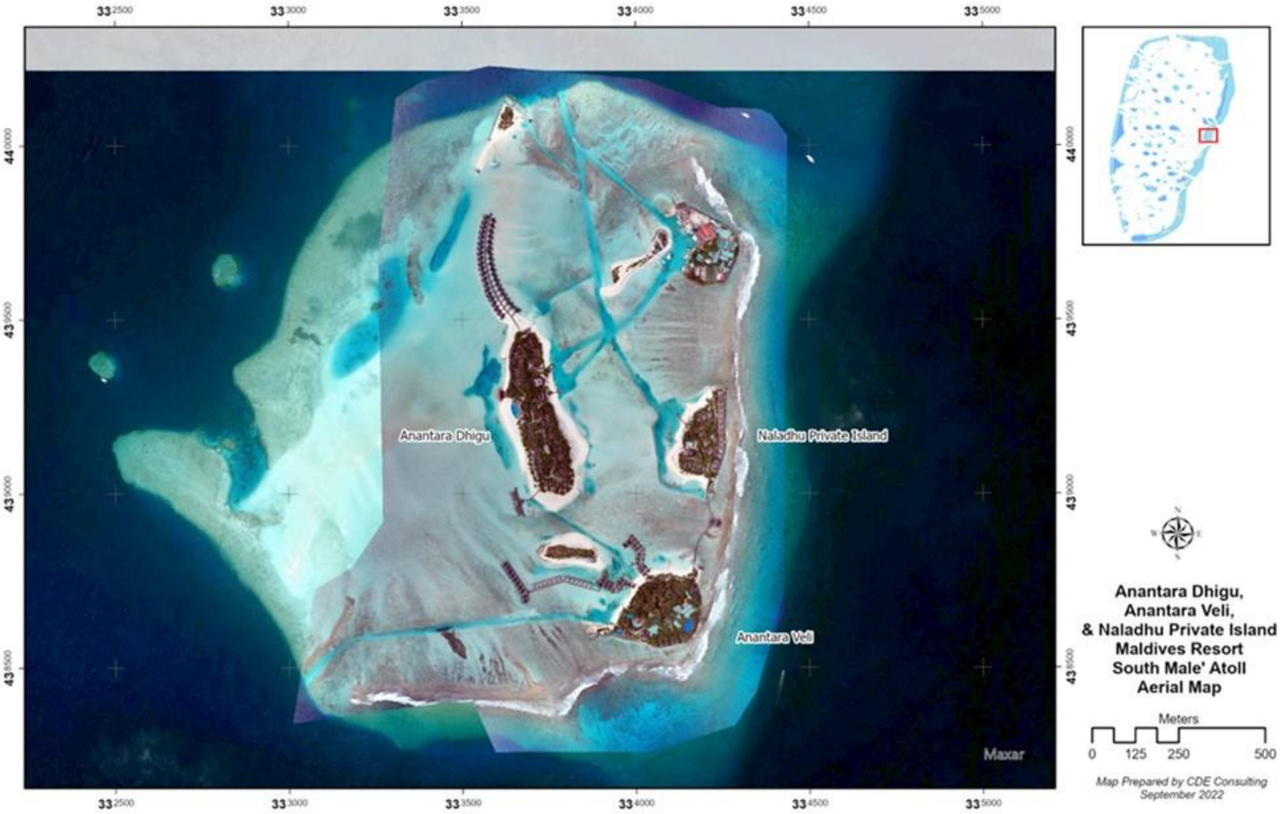

Figure 5 Satellite image of the islands

There are no protected areas or declared environmentally sensitive areas within this reef system. The nearest protected area is located about 9 km SW of the reef (Guraidhoo Kanduolhi) and the nearest environmentally sensitive area is Coco Thila located about 7 km SW of the reef. Map prepared by CDE consulting in September 2022.

4.2 Nursery designs and coral fragments

The nursery designs employed in the study were rope-based and table-based coral nurseries. Ropes-based nurseries were made of 2 metal staples 1 m × 2 m with ropes of a length of 8 m. Metal staples were made from stainless steel 316 bars (SS316) and welded from Anantara's Engineering Department on the island.

Each nursery supported 5 ropes. The ropes consisted of 8 mm twisted PP nylon (Veligaa Hardware, Maldives, approximately 500 kg~800 kg breaking strength) and hosted 25~30 coral fragments (Figure 6). Metal tables-based coral nurseries were square 1 m × 1 m, with a 10 cm × 10 cm grid, double coated with cement and sand to avoid the spread of rust and create a suitable substrate for the corals. The metal tables, welded on the island by Anantara's Engineering Department, were made of 8 mm iron rode bar. Each nursery hosted 25~30 coral fragments, with average 6~10 cm in length (Figure 6). Coral nurseries were deployed at 1.4 m~2 m (~2) and 4.6 m~5.1 m (~5) (depending on the tide level). The nursery was designed to do not exceed the natural height (about 40 cm) of natural coral rocks in the area. Tables-based and rope-based nurseries were located at approximately 4 m distance from each other.

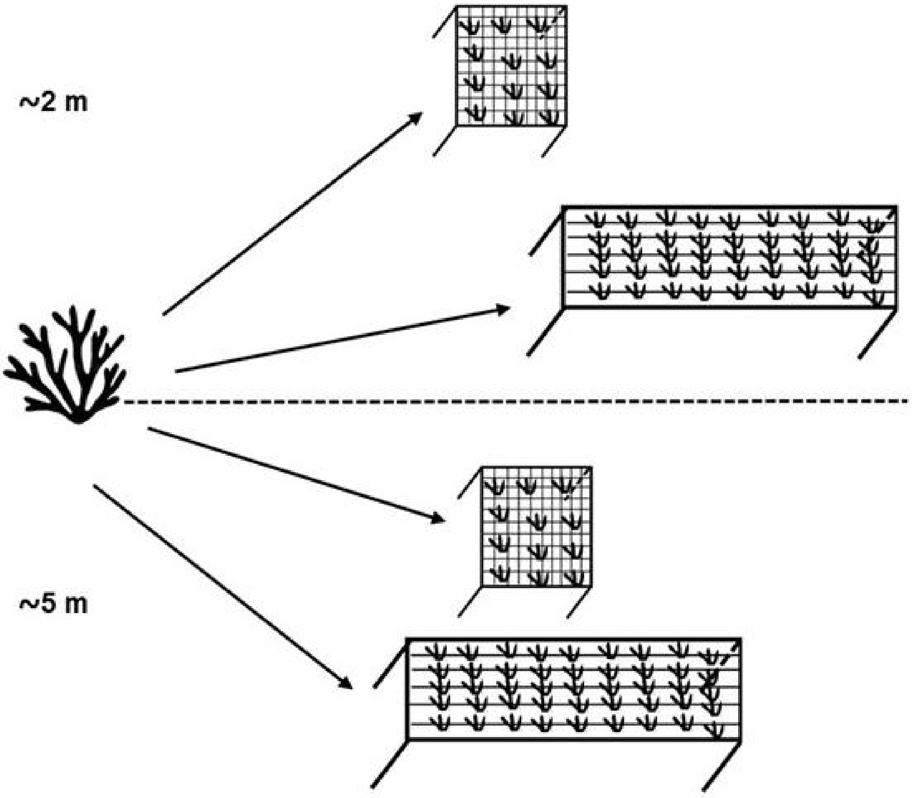

Figure 6 Scheme of the experimental design

The coral fragments utilized in the study were *Acropora aspera* (n=60), *Acropora muricata* (n=60) and *Montipora digitata* (n=60). Coral fragments used for the project were exclusively represented by pieces that break off naturally, for the action of animals (e.g. sea turtles, sharks, triggerfish) and humans (e.g. during maintenance/cleaning operations) and/or due to meteorological events (e.g. storms), within the same location as the nurseries. Fragments were carefully gathered and transported underwater by the operator in a perforated box to ensure adequate water flow and minimize damage during transit (2~7 min swim with scuba gear). Fragments from the same colony were evenly distributed between the rope and metal frames for consistency, having a total of 180 coral fragments (Figure 6). Coral fragments were attached to the ropes or metal frames with cable ties (3.6 mm × 200 mm). The first monitoring was carried out 1 week after the planting of the coral fragments to evaluate their response to mechanical stress, and then bimonthly (once every two months). Coral collection and planting was conducted according to NOAA Coral Bleaching Heat Stress Alert Area predictions. These activities were carried out only during the “no stress” phase, increasing the survival chances of the colonies.

Sea water quality was tested weekly onsite using HI98194 Multi-parameter Probe (HANNA Instruments, Singapore). The monitored parameters were Temperature, PH, Salinity, Conductivity and Dissolved Oxygen. No abnormal changes have been reported since 2016 in the study area and nearby coral reefs.

4.3 Data collection and analysis

Bimonthly underwater surveys were conducted over a period of six months, from September 2023 to March 2024, to analyze the following parameters: (i) growth rate, (ii) ecological volume, (iii) health condition, (iv) presence of disease, (v) predation, and (vi) survival rate.

During each underwater survey, the 180 coral fragments were measured by divers to the nearest millimeter with a Vernier caliper along the longest axis of the coral fragment to track their growth. The growth rate of the corals (Gr) was calculated with the formula Gr=T1-T0, where T0 represents the measurement of the fragment at time 0, and T1 represents the measurement of the same fragment at the subsequent time measured every 2 months.

The ecological volume (EV) was calculated by taking three measurements to the nearest mm using a Vernier caliper. $EV=\pi r^2 h$; where $r=(w+l)/4$ with 'h' representing the longest linear colony diameter of the three perpendicular measurements (h= height, w=width, l=length) (Shafir et al. 2006; Dehnert et al., 2022). Health condition (H) was recorded as follow: fragments with 100% living tissue (H3), more than 50% living coral tissue (H2), and less than 50% living tissue on the fragment (H1). Presence of diseases was also recorded by visual assessment (Dehnert et al., 2022; Pancrazi et al., 2023). In case of a suspected diseased coral fragment, a photo was taken to be analyzed. Predation was recorded when bitemarks or predation scars were evident on the fragments. Survival was determined as percentage (%) of coral fragments that survived after 6 months.

4.4 Statistical analysis

Statistical analysis was conducted in Graphpad Prism 8.0.2 Software, representing all data as arithmetic mean ± SD. Nonparametric tests were selected where normality assumptions were violated. Survival was compared using a Chi-square test of independence and Fisher's exact test. One-way ANOVA ($P < 0.05$) with Tukey's multiple comparisons test was used to analyze coral growth rates and other continuous variables across different nursery designs or depths. The assumptions of normality and homogeneity of variances were checked using the Shapiro-Wilk test and Levene's test, respectively. Graphs were created with Graphpad Prism 8.0.2 Software.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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