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Coral gardening in a changing climate: Rapid assessment of the 4th recorded bleaching event at the Anantara Lagoon and reef system, South Male Atoll, Maldives

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Abstract

Coral reefs are crucial to marine biodiversity and provide essential ecosystem services, but they face severe threats from climate change, particularly through coral bleaching events. The Maldives, renowned for its diverse coral reefs, has experienced increasing coral bleaching incidents, impacting both marine biodiversity and the tourism-dependent economy. This study investigates the effects of the 2024 coral bleaching event on coral nurseries within the Anantara Lagoon and reef system, South Male Atoll, Maldives. Monitoring was conducted across two coral nurseries in the lagoon and one coral nursery on the natural reef, focusing on species-specific responses to bleaching, predation, and survival rates. Results revealed variability in bleaching impacts among species and locations. *Acropora aspera* and *Acropora muricata* exhibited high mortality rates and increased predation, particularly at greater depths (~5 m), while *Montipora digitata*, *Pocillopora damicornis*, and *Porites cylindrica* showed greater resilience. The findings highlight the importance of adaptive management strategies for coral nurseries, emphasizing real-time environmental monitoring and strategic nursery placement to bolster coral reef resilience. This study underscores the need for integrated approaches combining coral restoration with broader reef management practices to enhance ecosystem recovery and sustainability.

Keywords: Coral reefs, coral bleaching, coral nursery, *Drupella* sp, climate change, resilient coral species

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Introduction

Coral reefs are among the most biodiverse ecosystems on the planet, providing critical services such as coastal protection, fisheries support, and tourism opportunities (Cinner et al., 2009; Migliaccio, 2024). As vital ecosystems, coral reefs sustain 25% of the marine life's biodiversity, much of which rely on the complex habitat structures formed by healthy coral colonies. However, the escalating frequency and severity of coral bleaching events, primarily driven by climate change, have emerged as one of the greatest threats to coral reef survival worldwide (Hoegh-Guldberg, 1999; Rochette et al., 2014; Sheppard et al., 2008). Coral bleaching, which occurs when corals expel their symbiotic zooxanthellae in response to stressors like elevated sea temperatures, disrupts the intricate balance of reef ecosystems (Smith et al., 2016; Wilkinson, 2008; van Oppen et al., 2015). Without these algae, which provide corals with essential energy, the corals lose their vibrant colors and experience diminished health, resulting in increased mortality rates, reduced reproductive success, and slower growth rates (Berkelmans & Oliver, 1999; Hughes et al., 2019; Albright et al., 2018; Kleypas et al., 2006).

The Maldives, renowned for its exceptional coral biodiversity, has witnessed a rise in coral bleaching events over the past few decades. These events have led to devastating ecological and socio-economic consequences. Coral reefs, which are a cornerstone of the nation's economy, particularly through tourism, have suffered considerable damage, threatening not only marine biodiversity but also the livelihoods of communities that depend on healthy reefs for fishing and tourism (Ibrahim et al., 2016). The 1998 coral bleaching event, exacerbated by an El Niño-driven rise in sea temperatures (~32 °C in May, NOAA Coral Reef Watch (available at https://coralreefwatch.noaa.gov/product/vs/data/maldives.txt), was the first and probably one of the most severe on record, with some reports indicating up to 90% coral mortality in shallow reef areas (Wilkinson & Souter, 2008; Bruno & Selig, 2007). In 2010, another episode of elevated sea surface temperature (~31 °C in April, NOAA Coral Reef Watch (available at https://coralreefwatch.noaa.gov/product/vs/data/maldives.txt), compounded by changes in oceanographic conditions, weakened currents and suppressed upwelling (McClanahan & Muthiga, 2011; Mallela & Beeden, 2011), affected the Maldives. Though less severe than 1998, it still caused significant coral bleaching and mortality, with some reefs in the northern and central atolls suffering up to 50% bleaching, while others showed less impact (McClanahan & Muthiga, 2011; Mallela & Beeden, 2011). In 2016, another significant bleaching event affected the Maldives, coinciding with one of the strongest El Niño events on record (Montefalcone et al., 2018). This event led to record-high sea surface temperatures (31 °C from March until May, NOAA Coral Reef Watch (available at https://coralreefwatch.noaa.gov/product/vs/data/maldives.txt; Montefalcone et al., 2018), contributing to widespread coral bleaching and mortality across the region, with some areas showing near-total coral loss. Many reefs saw coral mortality rates of up to 70%, particularly in the central and southern atolls (Montefalcone et al., 2018; Hooten, & Williams, 2017; Loya & Rinkevich, 2016). These recurring events have led to long-term degradation of coral cover, with severe implications for reef-associated biodiversity (Bellwood et al., 2004) and local economies (Gössling et al., 2006; Cinner et al., 2009).

Given the critical importance of coral reefs to the Maldives, monitoring projects and restoration efforts have become central to conservation strategies. These efforts include an extensive coral reef research program from the Maldives Research Institute (MRC) and the collaboration with UN Environment Programme (UNEP), World Bank, and Coral Cay Conservation on several coral reef conservation projects (http://www.mrc.gov.mv/en/programmes-and-collaborations/coral-reef-research-programme). Among the most promising techniques for restoring degraded coral ecosystems are coral gardening. Coral gardening involves cultivating corals in controlled environments, such as nurseries, before transplanting them to degraded reefs (Souter et al., 2018). These nurseries have become essential tools for mitigating coral loss and promoting reef recovery. Typically, they house juvenile corals or fragments from donor colonies (ranging from few mm to few cm in size, Dehnert et al., 2023; Hughes & Tanner, 2000), allowing coral to grow and develop in a protected environment. Once the corals reach a sufficient size (depending on the species, this may take 6 months to 2 years, Dehnert et al., 2023; Migliaccio, 2024), they are relocated to restore damaged reefs. However, coral nurseries themselves are not immune to the impacts of climate change.

Elevated sea surface temperatures (SST), which trigger bleaching events, can have several detrimental effects on nursery-grown corals. Increased SST can cause heightened mortality in nursery-grown corals, particularly if they have not been adequately acclimatized to fluctuating conditions (Anthony et al., 2011). In addition to increased mortality, the growth rates of corals in nurseries may be significantly reduced under stressful thermal conditions, delaying their development and making them less prepared for transplantation (Jones et al., 2004). Moreover, even when corals are successfully transplanted from nurseries to the wild, they often face challenges integrating into natural reefs. The stress of transplantation, combined with continued environmental stressors like warming waters, can compromise the health and resilience of these corals, impacting their survival and the overall success of restoration efforts (Rogers et al., 2014). This study aims to assess the impacts of the 4th recorded coral bleaching event in the Maldives on coral nurseries within the Anantara Lagoon and reef system, South Male Atoll. By examining how these nurseries have responded to the bleaching event, this research contributes to understanding the vulnerabilities and resilience of coral restoration efforts in the face of increasing climate-induced stress. The findings provide valuable insights into the effectiveness of coral gardening as a restoration strategy and highlight the urgent need for adaptive management practices in coral reef conservation.

Methods

Study area

The study was conducted in Anantara Maldives, located on a heavily modified reef system on the eastern rim of South Malé Atoll.

The reef system consists of four natural islands: Dhigu Finolhu (Anantara Dhigu), Bodu Huraa (Anantara Veli), Veligandu Huraa (Naladhu Private Island), and Gulhigaathuhuraa (housing the back-of-house facilities for the three resorts). In addition, there are three reclaimed islands—Gulhifushi (used for snorkeling), Moyo, and Alibe—which were created using sand dredged to form the access channels

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connecting the islands. A satellite image of these islands is shown Figure 1.

The bleaching monitoring focused on different areas: a) Anantara Dhigu coral nursery, GPS coordinates: 3.972885, 73.500920 (Permit number PA/CN-CR/2023/05; b) Anantara Veli Coral nursery, GPS coordinates: 3.968421, 73.504169 (Permit number PA/CN-CR/2023/06; c) Gulhifushi (Snorkel Island), GPS coordinates: 3.980541, 73.501791 (Permit number PA/CN-CR/2023/06).

Anantara Dhigu coral nursery is a shallow sandy area with a depth range between ~2 m (1.8 - 2.4 m, depending on the tide level) and ~5 m (4.9 - 5.5 m, depending on the tide level). The coral nursery is long approximately 100 m and wide 2 - 4 m and it distant approximately 678 m from the house reef. The restoration work in the area started in 2017, in collaboration with Aquafanatics (Silver Sands, Maldives) and the non-profit organization Coral Reef CPR (Conservation – Protection – Restoration, USA). The coral nursery hosted approximately 47 species of corals for a total of 3233 coral colonies.

Anantara Veli coral nursery is located between overwater villas and another island with vegetation (Moyo Island). This nursery is in a shallow sandy area, with a depth range between ~2 m (1.8 - 2.4 m, depending on the tide level) and ~5 m (4.9 - 5.5 m, depending on the tide level). The coral nursery is long approximately 100 m and wide 2 - 4 m and is distant approximately 300 m from the house reef. This nursery hosts approximately 1280 coral colonies.

Gulifushi housereef is a semi-continuous natural lagoon reef characterized by degraded areas on the top reef, heavily impacted by the 2016 coral bleaching event. Despite this, in the site there is an encouraging number of relatively small coral colonies, due to successful coral recruitment through natural coral spawning events after 2016 and approximately 5234 healthy coral colonies out planted from the coral nurseries.

Corals and nursery design

The coral colonies monitored in the study were *Acropora aspera* (n=60), *Acropora muricata* (n=60), *Montipora digitata* (n=60), *Pocillopora damicornis* (n=60), and *Porites cylindrica* (n=40) grown in 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 500-800 Kg breaking strength) and hosted 25-30 coral fragments. Metal tables-based coral nurseries were square 1 m × 1 m, with a10 cm x 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 an average of 6 to 10 cm in length.

Coral nurseries were deployed at ~2 and ~5 m. 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. Corals monitored were planted on September

Figure 1. 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, defined as an area vulnerable to activities such as tourism, overfishing, and climate-induced coral bleaching (UNEP, 2017) is Coco Thila, located about 7 km SW of the reef (www.googleearth.com).

2023, from 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. Coral fragments were attached to the ropes or metal frames with cable ties (3.6 x 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. Coral collection and planting were 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. (see Migliaccio, 2024 for more detailed information about the coral nurseries).

Data collection and analysis

Bleaching monitoring started in March 2024, according to NOAA Coral Bleaching Heat Stress Alert Area predictions. The parameters analyzed were a) bleaching status, b) presence of disease, c) predation, and d) survival rate. During each underwater survey, the operator recorded the extent of bleaching per colony (Gleason 1993): 1) No bleaching, 2)1-10% of the colony is bleached, 3) 11-50% of the colony is bleached, 4) 51-99% of the colony is bleached, 5) 100% bleached, 6) Dead.

The operator recorded also additional stressors visible or in the vicinity such as, macro algae or turf. In case of a suspected diseased coral fragment, a photo was taken to be analyzed. The suspected fragment was carefully removed from the nursery and isolated. Predation was recorded when bitemarks or predation scars were evident on the fragments. Survival was determined as percentage (%) of coral fragments that survived after the bleaching event (after 6 months).

Statistical analysis

Data are presented as percentages (%). The Kruskal-Wallis test ($p < 0.05$) was used to analyze the data. Survival was compared using a Chi-square test of independence and Fisher's exact test. Statistics was performed with Graphpad Prism 8.0.2 Software.

Results

Sea surface temperature

Sea surface temperature (SST) started increasing at the end of March 2024, reaching 31 °C in April 2024 (Figure 2). The average sea surface temperature returned to values below or around 30 °C in September 2024.

Bleaching status

For *A. aspera*, the first signs of bleaching appeared in late March, in Dhigu coral nursery, intensified though May and peaked in June and July with 70% of the coral colonies fully bleached. Most of the coral colonies in Dhigu at ~2 m were found dead by the beginning of August. The colonies at ~5 m had overall a lower mortality rate (30%) compared to the colonies located at ~2 m (Figure 3).

In Veli coral nursery, similar temporal patterns were noted. However, bleaching and mortality were higher at ~5 m, compared to ~2 m (Figure 3).

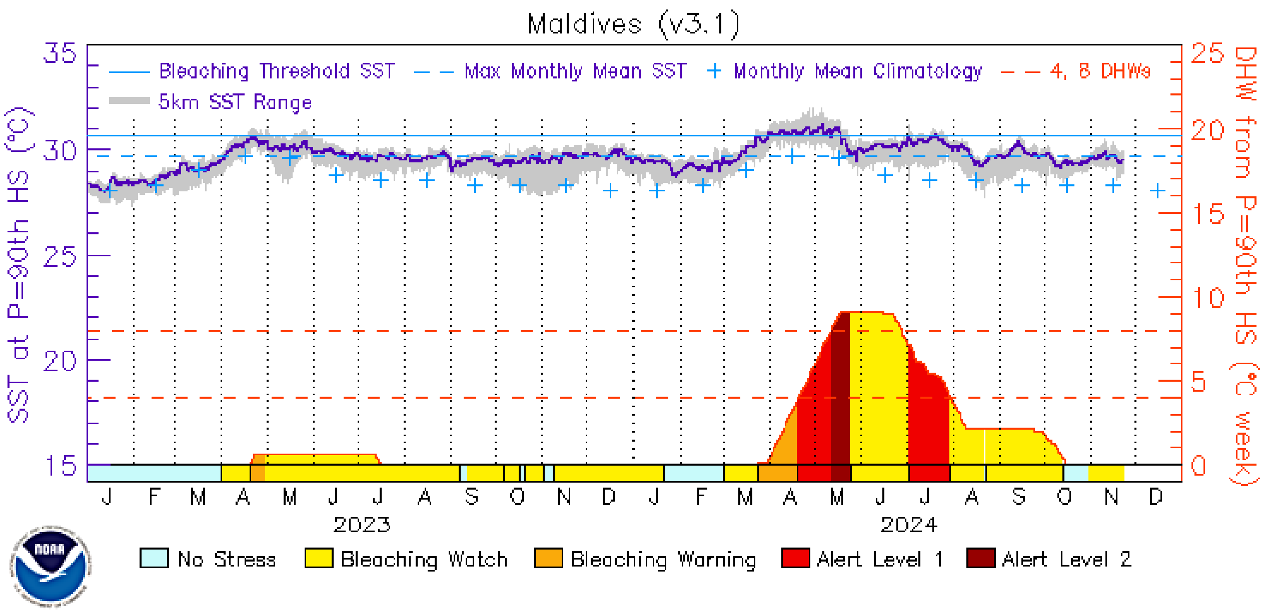

Figure 2. Sea surface temperature for the Maldives in 2023 and 2024, reported by NOAA Satellite and Information Service (available at https://coralreefwatch.noaa.gov/product/vs/gauges/maldives.php).

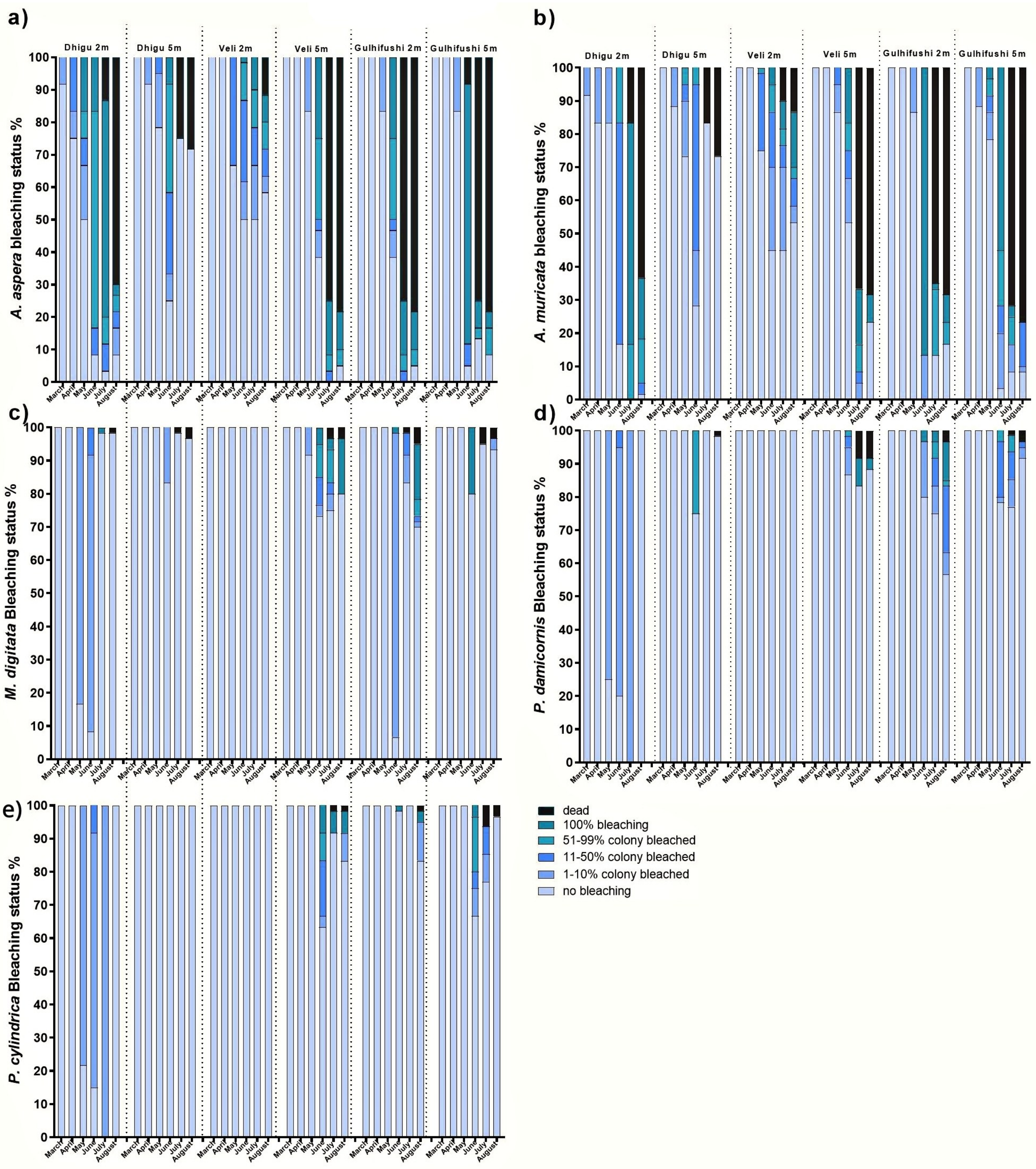

Figure 3. Bleaching status of *A. aspera* (n=60), *A. muricata* (n=60), *M. digitata* (n=60), *P. damicornis* (n=60), and *P. cylindrica* (n=40) in Anantara Dhigu, Anantara Veli and Gulhifushi at ~2 and ~5 m from March to August 2024. The extent of bleaching per colony was recorded following Gleason (1993) as follow: 1) No bleaching, 2) 1-10% of the colony is bleached, 3) 11-50% of the colony is bleached, 4) 51-99% of the colony is bleached, 5) 100% bleached, 6) Dead. One-way ANOVA, Tukey's post hoc test ($p < 0.05$). Chi-square and Fisher's exact test ($p < 0.05$). N=60.

In Gulhifushi, bleaching occurred later (in May), but overall coral mortality was higher at both ~2 m and ~5 m depths compared to the other coral nurseries (Figure 3).

For *A. muricata*, the initial bleaching signs at Dhigu ~2 m were noted at the end of March. By July, nearly 80% of the colonies were fully bleached, with mortality reaching approximately 70% by August (Figure 3). At ~5 m, the pattern was similar, but the mortality rate lower (25%).

In Anantara Veli, bleaching affected 65% of colonies at ~5 m by August, with a lower mortality rate (15%) at ~2 m (Figure 3). Mortality surpassed 50% by July and reached 60% by August (Figure 3).

In contrast, *M. digitata*, *P. damicornis* and *P. cylindrica* responded differently to the bleaching event and no major differences were found between ~2 and ~5 m. In Dhigu, initial bleaching was noted in April and May, with over 80% of colonies exhibiting various bleaching intensities by July (Figure 3). In Veli, bleaching affected 20% of colonies at ~5 m in July, but mortality rates were low (Figure 3). In Gulhifushi, the mortality rates remained under 20% (Figure 3).

No diseases were observed in the monitored species during the six-months study period.

Predation rate

Predation rates varied across species and depths, showing distinct patterns in different nurseries. In Dhigu coral nursery, a high predation rate was recorded for *A. aspera* at ~2 m (July, 20 -30%, Figure 4). In contrast, low predation rate was recorded at ~5m. For *A. muricata* the increase in the predation rate was found from July in Dhigu, Veli and Gulhifushi especially at ~2 m (Figure 4). At ~5 m, higher predation rates were recorded in Veli (20%, Figure 4). In contrast, *M. digitata*, *P. damicornis*, and *P. cylindrica* showed no predation recorded across any of the study sites (Figure 4).

No predation was recorded on rope-based nurseries.

Survival rate

Survival rate, determined as percentage (%) of coral fragments that survived after the bleaching event, was influenced by location and species.

In Dhigu coral nursery, 30% of *A. aspera* colonies survived at ~2 m and 70% at ~5 m (Figure 5). In Veli coral nursery, the survival rate was significantly lower at ~5 m (20%) compared to ~2 m (80%), whereas in Gulhifushi, no significant differences were found between different depths (approximately 20%, Figure 5). *A. muricata*, showed a very similar pattern, with

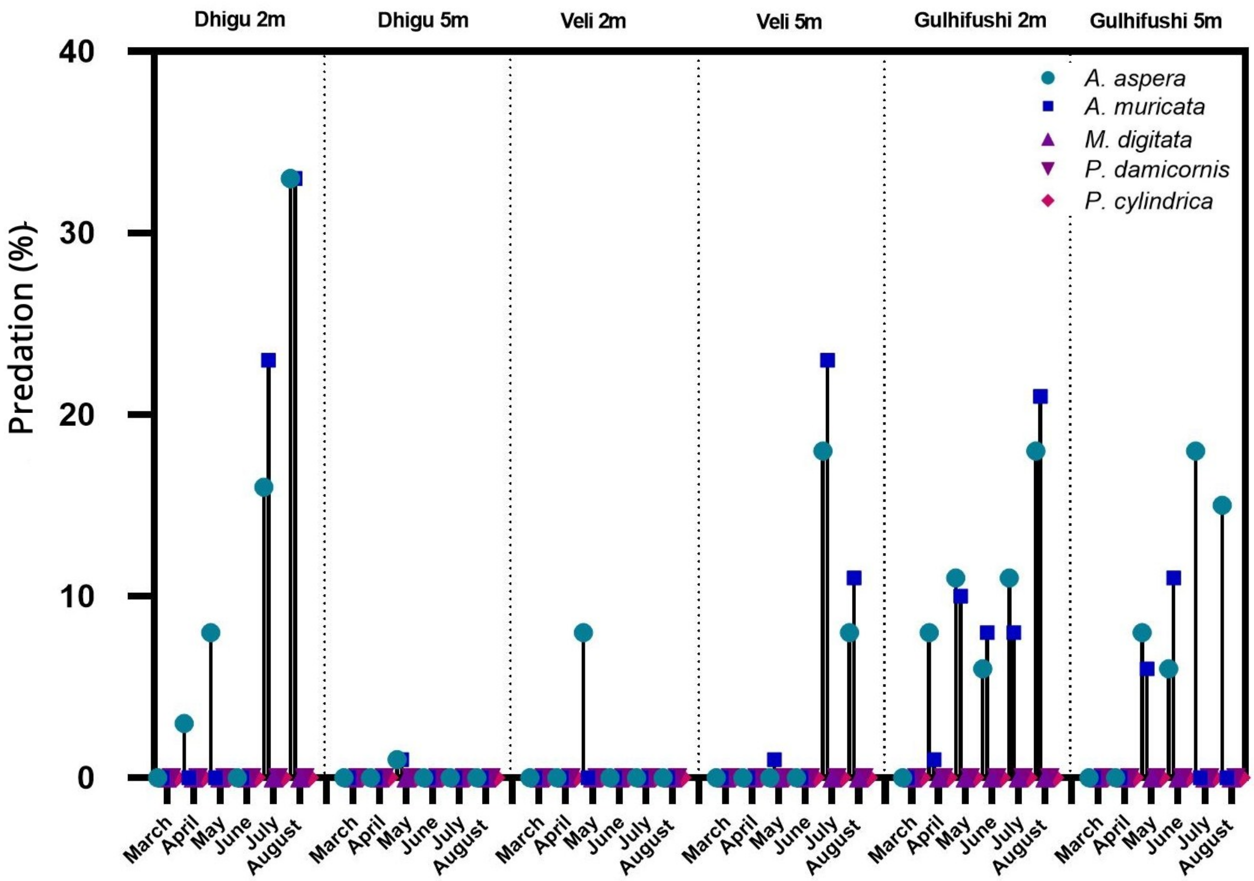

Figure 4. Predation (%) for *A. aspera* (n=60), *A. muricata* (n=60), *M. digitata* (n=60), *P. damicornis* (n=60), and *P. cylindrica* (n=40) in Anantara Dhigu, Anantara Veli and Gulhifushi at ~2 and ~5 m from March to August 2024. Predation was recorded when bitemarks or predation scars were evident on the fragments. One-way ANOVA, Tukey's post hoc test ($p < 0.05$). Chi-square and Fisher's exact test ($p < 0.05$). N=60.

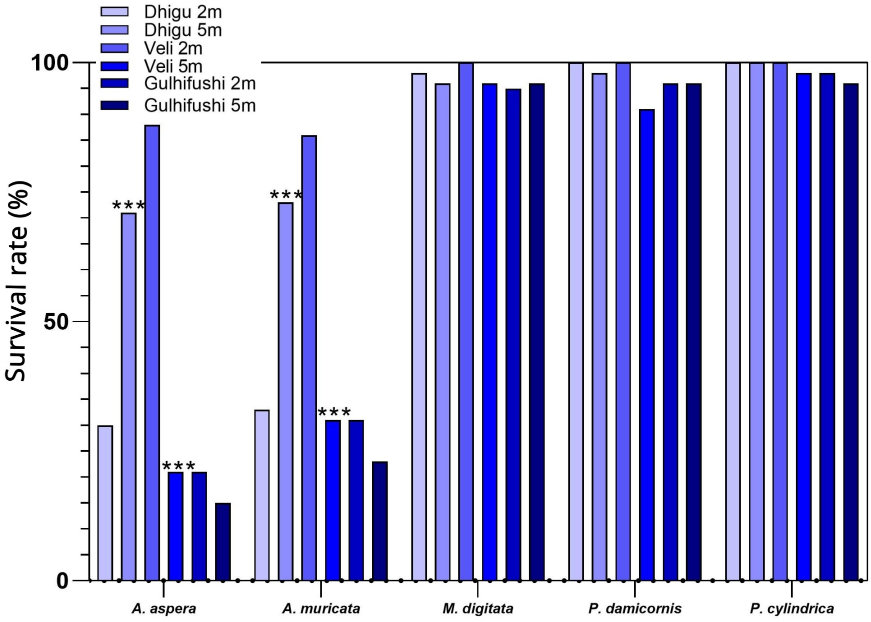

Figure 5. Survival rate (%) of *A. aspera* (n=60), *A. muricata* (n=60), *M. digitata* (n=60), *P. damicornis* (n=60), and *P. cylindrica* (n=40) in Anantara Dhigu, Anantara Veli and Gulhifushi at ~2 and ~5 m from March to August 2024. Survival was determined as percentage (%) of coral fragments that survived after the bleaching event (6 months). Survival was compared using a Chi-square test of independence and Fisher's exact test (N=60).

higher survival rate at ~5 m in Dhigu coral nursery (70%). Similarly, for *A. muricata* in Veli coral nursery, the survival rate was higher at ~2 m (85%) compared to ~5 m (30%), whereas in Gulhifushi, no significant differences were found between different depths (approximately 30%, Figure 5). *M. digitata*, *P. damicornis* and *P. cylindrica* showed a very high survival rate in all the locations and depths (above 80%, Figure 5).

Discussion

The 2024 coral bleaching event in the Maldives has revealed significant insights into the impact of thermal stress on coral nurseries, particularly within the Anantara Lagoon and Gulhifushi reef system. Our findings underscore the varying resilience of different coral species to bleaching, influenced by factors such as location and predation pressure (Baird, 1999; Baird & Marshall, 2002; Montefalcone et al., 2020).

Acropora species exhibited the highest levels of bleaching and mortality, consistent with previous studies indicating their higher susceptibility to thermal stress (Berkelmans & Oliver, 1999; Hughes et al., 2018). The bleaching status and the mortality rate were not directly correlated to the depth; however, the variations were found to be location dependent. Indeed, the bleaching status and the mortality rate in Dhigu coral nursery were higher at ~2 m compared to ~5 m, but in Veli coral nursery opposite were observed, with higher mortality at ~5 m. In Gulhifushi, the bleaching status and the mortality rate were similar at both depths. These results are in line with previous studies suggesting that other environmental conditions play an important role in mitigating or exacerbating the effects of bleaching events (Montefalcone et al., 2018). For example, a reduced water exchange has been demonstrated to exacerbate the stress experienced by corals (Anthony et al., 2011). Similarly, high nutrient levels cause an increase in coral mortality following bleaching events (Montefalcone et al., 2018).

Interestingly, predation rates were also higher in Dhigu coral nursery at ~2 m and in Veli coral nursery at ~5 m and were similar in Gulifushi at both depths. The higher predation rates could contribute to the higher mortality rate observed in the coral nurseries. *Drupella* snails, are well-known for their predatory behavior on coral reefs, especially during periods of coral stress (Mc Cook et al., 2001). These snails feed on corals, and their predation can be particularly harmful during bleaching events. When corals are stressed by elevated temperatures (leading to coral bleaching), their immune defenses and overall health are compromised, making them more vulnerable to predation. Several studies have demonstrated that coral species under bleaching event experience increased predation pressure as their resistance to predators decreases (Zhang et al., 2024; Bruckner et al., 2017).

The reduction in predation and the higher resilience observed in Dhigu coral nursery at ~5 m and in Veli coral nursery at ~2 m, could be associated to damselfish algal dawns reported in those areas, but not recorded in Gulhifushi. The algal lawns could indeed help corals during bleaching events, especially by preventing harmful algae from overwhelming the corals. Damselfish graze on turf algae and defend their algal lawns from other herbivores, maintaining a balance that can reduce competition for space and light. As a result, they provide a more favorable environment for corals, such as *Acropora*, to recover from bleaching (Bellwood et al., 2004; Dailer et al., 2012; Shantz & Burkepile, 2014). Moreover, macroalgae have been demonstrated to play a supportive role in the recovery of some *Acropora* colonies (Burkepile & Hay, 2006). However, the potential buffering effect, the positive effects of algal lawn on coral colonies and on *Drupella* predation merits further investigation. *M. digitata*, *P. damicornis*, and *P. cylindrica* demonstrated greater resilience to the bleaching event, confirming their high tolerance to thermal stress and the ability to recover more effectively

(Hughes et al., 2018). Some coral species, including *Pocillopora*, can shut down and shift the composition of their symbiotic algae during periods of stress, reassociating with more heat-tolerant strains of zooxanthellae. This dynamic shift in symbiotic algae composition can be a major determinant of coral survival and recovery during periods of high thermal (Berkelmans & Oliver, 1999; Carballo-Bolanos et al., 2019). Species like *P. cylindrica* and *M. digitata* possess robust skeletal structures, which are thought to provide physical protection against thermal fluctuations and enhance structural integrity during coral bleaching (Montefalcone et al., 2020). This structural resilience helps corals recover faster as it supports the regrowth of tissues and facilitates the recolonization of zooxanthellae (Berkelmans & Oliver, 1999).

Conclusions

The 2024 coral bleaching event in the Maldives has highlighted the complex interplay of factors that influence coral resilience to thermal stress, emphasizing the role of species-specific traits, environmental conditions, and biological interactions. Our findings demonstrate that coral species exhibit varying degrees of susceptibility to bleaching, with *Acropora* species being particularly vulnerable, while *M. digitata*, *P. damicornis*, and *P. cylindrica* showed greater resilience due to factors such as robust skeletal structures and higher thermal tolerance.

Depth-dependent variations in bleaching and mortality rates further underscore the influence of local environmental conditions, such as nutrient levels, and water exchange, in determining coral survival during thermal stress. Additionally, the observed predation pressures from herbivores, particularly *Drupella* snails, further compounded the stress on corals, making them more vulnerable during bleaching events. However, the presence of damselfish algal lawns in certain nurseries suggests a potential buffering effect that could help mitigate some of the negative impacts of bleaching and predation by maintaining a balanced environment for coral recovery. This interplay between herbivory, algal competition, and coral resilience warrants further investigation to better understand how biological interactions and environmental factors can be leveraged to enhance coral reef resilience in the face of ongoing climate change. As coral reefs continue to face the increasing threat of thermal stress and bleaching events, the insights gained from this study can inform strategies for coral conservation and management, particularly in understanding how species-specific traits and habitat conditions contribute to the survival and recovery of coral ecosystems.

These findings emphasize the importance of adaptive management strategies for coral nurseries, including real-time monitoring of environmental conditions, diversification of coral species, and strategic nursery placement. By integrating these approaches with broader reef management practices such as Marine Protected Areas (MPAs) and pollution control, it is possible to enhance coral reef resilience and improve the effectiveness of restoration efforts as suggested in several studies (Gell & Roberts, 2003; Chong-Seng et al., 2012; Montefalcone et al., 2018; Montefalcone et al., 2020; McClanahan et al., 2009; Mora et al., 2011; Rochette et al., 2014; Munday & McCormick, 2008). Implementing comprehensive monitoring programs and early warning systems will be crucial for anticipating and responding to future bleaching events, ultimately contributing to the preservation and restoration of these vital marine ecosystems.

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Authorship contribution

Oriana Migliaccio: Conceptualization, methodology, investigation, resources, sample processing and analysis, data curation, formal analysis, visualization, original draft preparation writing, review and editing. Author gave final approval for publication and agreed to be held accountable for the work performed therein.

Data availability

Datasets generated during and/or analysed throughout the present study are available from the corresponding author upon reasonable request.

Conflict of interest

The authors declare no conflict of interest.

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