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# *Acropora* spp. Coral Gardening Using Fragmentation and Direct Transplantation: A Feasibility Study at Boundary Island

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## Abstract

As major bleaching continues to ravage reefs worldwide, there is an urgent need for active coral restoration. However, the high cost of such a project is inhibitive for many countries. Here, we introduce a cost-effective design for *Acropora robusta* and *Acropora valenciennesi* coral gardening through fragmentation and direct transplantation. Implemented off Boundary Island, Hainan Province, China, the project demonstrated high coral survival rates (>94%) at a reduced cost of USD 2.50 per coral after 246 days, besides exhibiting an efficient outplanting rate at 30 coral $h^{-1}$ $person^{-1}$. Growth monitoring suggested that the transplanted *Acropora* spp. follow an exponential growth model over time. Initial fragment size did not seem to affect the growth rate of outplanted *Acropora* spp., although a weak negative correlation was found at day 246 for *A. robusta*. Finally, the design used in this study employs detachable steel grid nurseries and is plastics-free, ensuring sustainability and adaptability to different reef conditions, and thus providing a promising strategy for affordable coral reef restoration.

**Keywords:** reef restoration; fragmentation; direct transplantation; growth model; cost-effective design; *Acropora* spp.; sustainability

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## 1. Introduction

Record high temperatures in recent years [1] have contributed to increased major bleaching events [2–5] in coral reefs around the world. The rapid occurrence of thermal stress could overwhelm the adaptation mechanism of corals, reducing their ability for natural recovery, which in turn would lead to greater rate of reef degradation [6]. While natural recovery from bleaching is possible in many cases, it is not guaranteed to occur. Furthermore, fast-growing competitors such as macroalgae, turf algae and crustose coralline algae could outcompete native corals in degraded reefs, causing a spatial community shift that would ultimately diminish their ecosystem functionalities [5,7]. Various intervention strategies such as selective breeding and assisted evolution have been explored to increase climate resilience in corals. However, these efforts face significant cost and scalability

issues [8,9], besides the challenges to maintain the desired resilience beyond the modified generation due to the lack of clarity on their molecular mechanisms [10]. Alternatively, coral gardening has emerged as a popular strategy for relevant authorities to restore degraded reefs due to its scalability [11–13]. The coral gardening method involves propagating a substantial number of coral colonies in nurseries until they attain appropriate sizes, by which they are outplanted onto damaged reef, and thus quickly repopulate the bleached reefs when the conditions are favorable. While the use of coral fragments for stable propagation has been in practice for years, the collection of wild coral fragments poses the dilemma of causing ecological damage to other sites [14]. In this aspect, the emergence of micro-fragmenting as a viable technique has greatly enhanced the efficiency of coral asexual propagation while simultaneously reducing the ecological cost of coral fragments [15,16]. There has been extensive research on coral nursery methods, indicating that over 100 coral species can be successfully cultivated using different nursery prototypes. On the other hand, the transplantation of corals has not been as extensively studied, leaving many theoretical and practical aspects yet to be explored [17,18].

However, coral mortality, economic and ecological costs are prohibitive issues for many coral gardening programs [12,19,20]. The prevailing approach in coral outplanting involves manually affixing each fragment to a base, typically a flat surface. This process is labor-intensive and time-consuming, thereby restricting its application primarily to smaller-scale projects. Moreover, in many degraded reef regions, the substrates are not optimal for coral attachment due to issues like dynamite fishing (rubbles) and sedimentation from land reclamation (sandy) [17], which significantly reduces the success rate of outplanting. Additionally, the practice of planting individual colonies fails to leverage one of the key benefits of in situ coral nurseries. Unlike ex situ nurseries, in situ nurseries can also serve as habitats that attract reef-associated organisms [21,22], thus promoting the biodiversity of reefs. The survivorship of transplanted corals is highly variable, ranging from 16.6% to 100%, depending on the species [17,23,24]. This variability not only complicates restoration efforts but also increases the financial burden, with the estimated cost of restoration per coral fragment ranging from USD 4 to over USD 60 [20,25,26]. Furthermore, the use of plastic materials, such as cable ties, to secure coral fragments to the substrate poses significant environmental concerns [12,19,27,28]. Given these challenges, there is an urgent need to promote the development of low-tech, cost-effective, and environmentally friendly coral gardening and transplantation practices to ensure the sustainability and scalability of coral restoration programs.

Here we aim to evaluate the efficacy and feasibility of a trial coral gardening project on Boundary Island, Hainan Province, China that uses in situ coral nurseries. The combination of coral fragmentation and direct outplanting used in our trial is simple, economical and sustainable. The choice of materials and structural designs in our study are made in consideration of the local climate conditions, which experiences an annual typhoon season. Besides the financial cost, this study also aims to investigate the impact of fragmentation size on the success of coral gardening. As such, the growth and survival rate of the corals are measured periodically to determine whether fragments of different sizes show different growth dynamics. The results from our study demonstrate a cost-effective coral propagation and transplantation method that is feasible for areas with less-than-ideal climate and reef substrate.

## 2. Materials and Methods

### *2.1. Restoration Site*

The site chosen for the coral gardening is Boundary Island (18.5772° N, 110.1966° E), located in Lingshui County, Hainan Province, China, with an average sea surface tempera-

ture (SST) of 24.8 °C. Coral fragments were collected from corals from established nurseries constructed in an area near the restoration site.

### *2.2. Coral Reef Survey*

The survey on coral reef was carried out using the line intercept transect (LIT) method. Specifically, a 50 m-long measuring tape, marked at 1 cm intervals, was laid out over a flat transect area. An underwater digital camera was used to film along the length of the tape from one end to the other. After photography and videography, the coordinates of both ends of the transect were recorded to provide accurate locations for future monitoring. The footage was then analyzed to identify and quantify the reef organisms, and to measure the length of live corals beneath the tape, excluding those less than 5 cm long.

### *2.3. Coral Species Identification*

Coral species were preliminary identified based on photographs, supplemented by video footage, in situ observations, and specimen collection. The initial identification of coral species was performed by examining coral morphology and sclerite characteristics (for soft corals). If species identification could not be made visually, molecular techniques, such as DNA barcoding, were further employed for species determination.

### *2.4. Studied Species*

Two *Acropora* species, *Acropora robusta* and *Acropora valenciennesi*, were selected for our coral gardening project. These species are the predominant reef-building corals found in Boundary Island, and their fragments are readily available from established nurseries near the designated restoration site.

### *2.5. Construction of Coral Nurseries*

Coral fragments were transplanted to the restoration site using a modular grid assay. The grid assay is made of flat and L-shaped perforated stainless-steel bars assembled into a 1 m × 1 m tabletop frame (Figure 1) that serves as a coral nursery. Each horizontal bar could attach 8 to 10 propagation plugs for attachment using screws. The propagation plug used in this study was a hemispherical dome with a diameter of 34 mm, featuring a central hollow column with a diameter of 22.5 mm and a height of 17.5 mm, and can be used either individually or as screw-on to the grid assay. During transplantation, the frame can be supplemented with four V-shaped angle steel bars (0.5–1 m) that act as anchorage for sandy substrate.

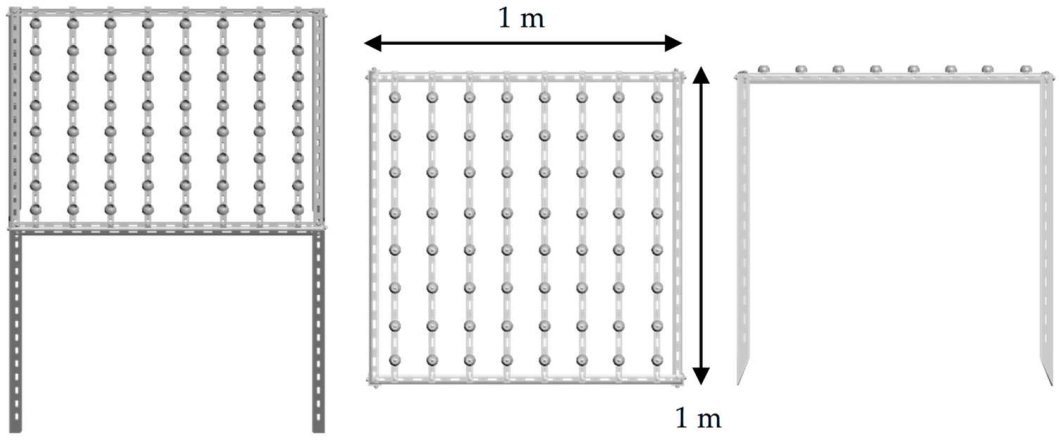


**Figure 1.** Schematics for grid assay. The bars are made of 304-grade stainless steel and are detachable.

### 2.6. Coral Fragmentation

Healthy corals were selected as parent stocks. In order to study the effects of fragment size on the growth of coral outplants, fragments varying from 23 mm to 93 mm long were excised from selected corals using a garden shear. Excised fragments were placed immediately into tanks containing seawater for transport. The fragments were then secured onto the attachment plugs using cyanoacrylate-based adhesive (Coral glue, Maxspect, Hong Kong, China), before being screwed onto the grid assay. Seawater was continuously sprayed onto the fragments during fixation to maintain the moisture.

### 2.7. Coral Transplantation and In Situ Nursery

Coral transplantation was carried out immediately after fragment fixation, either by grid nursery or individual plugs. For grid nursery transplantation, the coral nurseries were transplanted onto the restoration site at 3–5 m water depth. Outplanting for individual coral fragment was also performed by removing the plugs from the grid and fixed on the substrate at 3 m water depth using 1.5-inch stainless steel nails. Grid nurseries were outplanted on 7 November 2023, while individual plugs were outplanted on 27 April 2024. The height of the coral transplants in grid nursery was measured at day 172, 223 and 246, while height of coral transplants in the individual plugs was measured at day 20, 51 and 115 using photography.

### 2.8. Costing Exercise

Cost calculation in this study is focused on the setup of in situ nurseries and transplantation cost. The wage rate for personnels involved are as follows: researcher (USD 120 $d^{-1}$), diver (USD 170 $d^{-1}$), boat crew (USD 65 $d^{-1}$), and trained manual labor/graduate students (USD 33 $d^{-1}$). Dive equipment was rented at USD 20 $person^{-1}$. Boat rental was quoted at USD 800 $d^{-1}$, inclusive of fuel. Working meals (lunch and dinner) were provided daily at USD 5 per meal. The currency exchange rate from Chinese yuan (¥) to USD is set as 7:1.

### 2.9. Data Analysis

The height of coral transplants was taken as the growth indicator and were estimated from images taken using ImageJ (version 1.54p, University of Wisconsin, Madison, WI, USA). Measurements were taken from the rim of the propagation plug to the apical tip of the coral fragment. Calibration of measurements were performed against the base of the propagation plug which is 2.3 cm in diameter. Results are presented as mean $\pm$ SD where applicable. Data analysis and graphical representations were generated using GraphPad Prism 8.0.2. Significant differences were calculated using one-way analysis of variance (ANOVA) with Tukey's multiple comparisons test, while correlation was assessed using Pearson correlation coefficient. All analyses were performed at $p < 0.05$ unless stated otherwise.

## 3. Results

### 3.1. Coral Reef Survey Results

In 2024, the initial survey of coral reefs at Boundary Island had found that the hard coral coverage ranged from 0.40% to 30.2%, with an average coverage of 13.15%, down from 17.60% from the previous year. There was a total of 56 species of reef-building corals, belonging to 13 families and 20 genera, and 3 species of soft corals. The recruitment rate of hard corals was very low, found only at three sites, with an average of 0.08 individuals per square meter. There were seven species of large benthic organisms. No coral predators were found, but some sites showed signs of coral bleaching. Post-transplantation survey suggests that the number of reef-associated fish increased by 21%.

### 3.2. Ex Situ Nursery

All corals selected for fragmentation in the ex situ nursery were in good health. No signs of disease were observed on the corals prior to transplantation.

### 3.3. Coral Transplantation, Survival and Growth

A total of five grid nurseries were assembled for *A. robusta* (5 grids, $n$ = 443) and *A. valenciennesi* (one grid, $n$ = 33) and transplanted to the designated restoration site (Figure 2a–c). Coral transplantation using individual plug was also performed ($n$ = 21 and $n$ = 6 for *A. robusta* and *A. valenciennesi*, respectively, Figure 2d). Overall, all corals showed consistent growth (Figure 3) during the period of experiment, with no signs of bleaching. However, for grid nurseries, 24 transplants of *A. robusta* were lost at some point during the experiment due to detachment from the propagation plugs, while 4 transplants were snapped during the monitoring period (Table 1). Unfortunately, due to Typhoon Yagi making landfall on 7 September 2024 (day 306 post-outplanting), the experiment was forced to an abrupt stop.

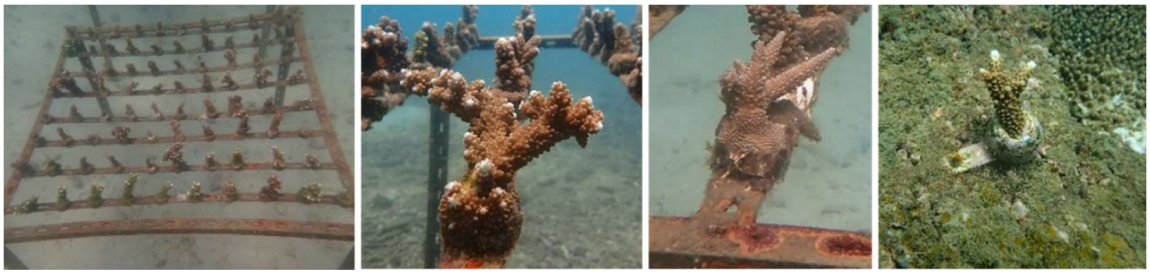


**Figure 2.** The coral transplantation: (**a**) a grid nursery; (**b**) *A. robusta*; (**c**) *A. valenciennesi*; (**d**) individual plug.

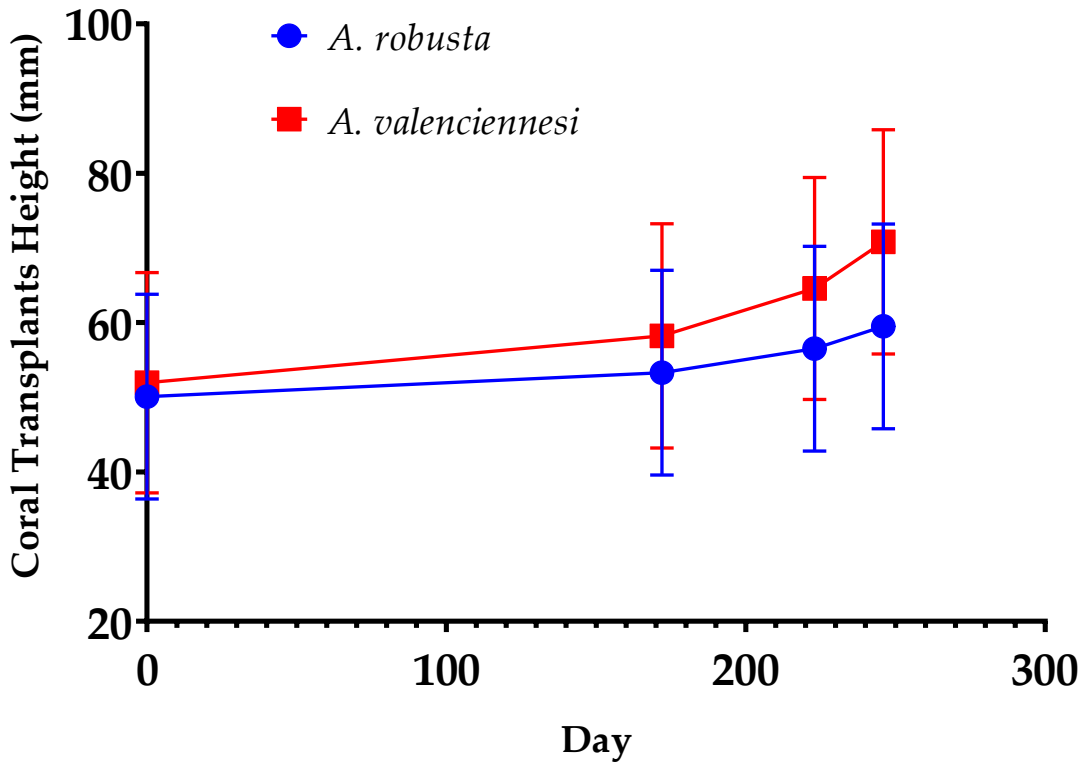


**Figure 3.** The changes in height of *A. robusta* ($n$ = 418) and *A. valenciennesi* ($n$ = 33) transplants in grid nursery assay at day 0, 172, 223 and 246.

**Table 1.** Survival rate of coral transplant.

| Species | Transplantation Method | Number of Transplants | Survived Transplants | Survival Rate (%) |
|---|---|---|---|---|
| *Acropora robusta* | Grid assay | 443 | 419 | 94.58 |
| *Acropora valenciennesi* | Grid assay | 33 | 33 | 100 |
| *Acropora robusta* | Individual plug | 21 | 21 | 100 |
| *Acropora valenciennesi* | Individual plug | 6 | 6 | 100 |

### 3.4. Species Impact on Growth Rate

Both species displayed increasing annual growth rate over time, with *A. valenciennesi* significantly outgrowing *A. robusta* across all time points. Overall, *A. robusta's* annual growth rates were 6.838 ± 1.772, 22.93 ± 6.286 and 47.60 ± 11.88 mm $yr^{-1}$ at day 176, 223 and 246, respectively, while *A. valenciennesi* registered annual growth rates of 13.30 ± 1.611, 45.26 ± 14.56 and 99.19 ± 13.73 mm $yr^{-1}$ at the corresponding days (Figure 4).

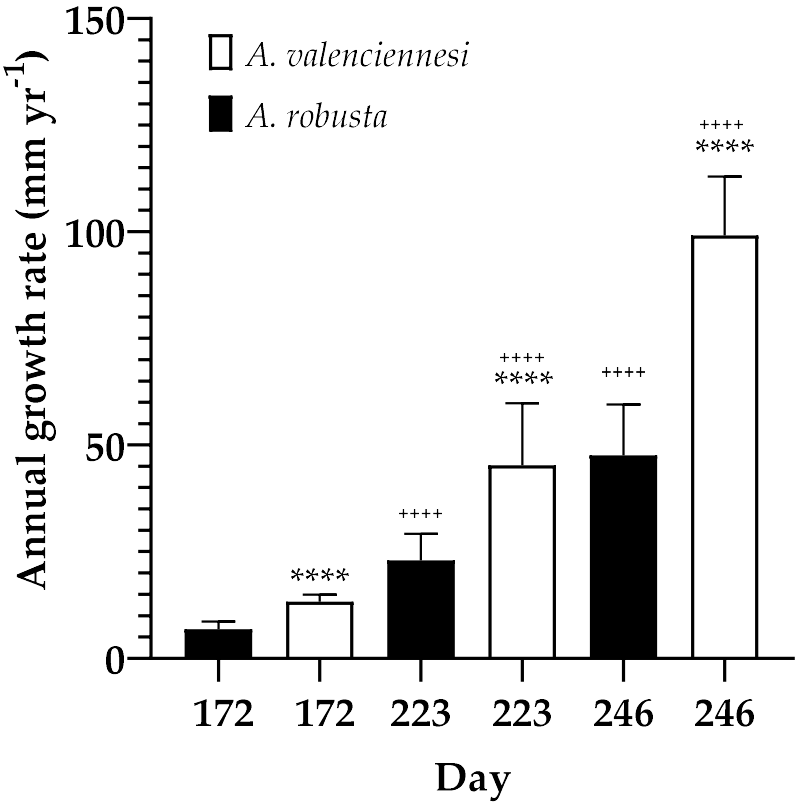


**Figure 4.** Comparison of annual growth rate of achieved by *A. robusta* (*n* = 414) and *A. valenciennesi* (*n* = 33) using grid assay post-transplantation at different time points. **** Denotes statistical significance between species of same period; ++++ denotes statistical significance between days of same species ($p > 0.0001$).

### 3.5. Fragment Size Impact on Growth Rate over Time

The annual growth rate of both corals was not significantly correlated to the initial height of transplant, except for day 246 of *A. robusta*, which showed a week negative correlation with initial height (Figure 5a,b, Pearson r = −0.09643, $p = 0.0499$). Although the Pearson r value for *A. valenciennesi* on day 172 is 0.3191, its small sample size meant that the relationship was not considered as significant ($p = 0.0703$). Linear regression analysis also indicates that the change in height of *Acropora robusta* coral fragments is nearly proportional to their initial height, with a consistent growth rate across different initial fragment sizes (Figure 5c,d), albeit with the $R^2$ values for both corals gradually deviating from 1 over time.

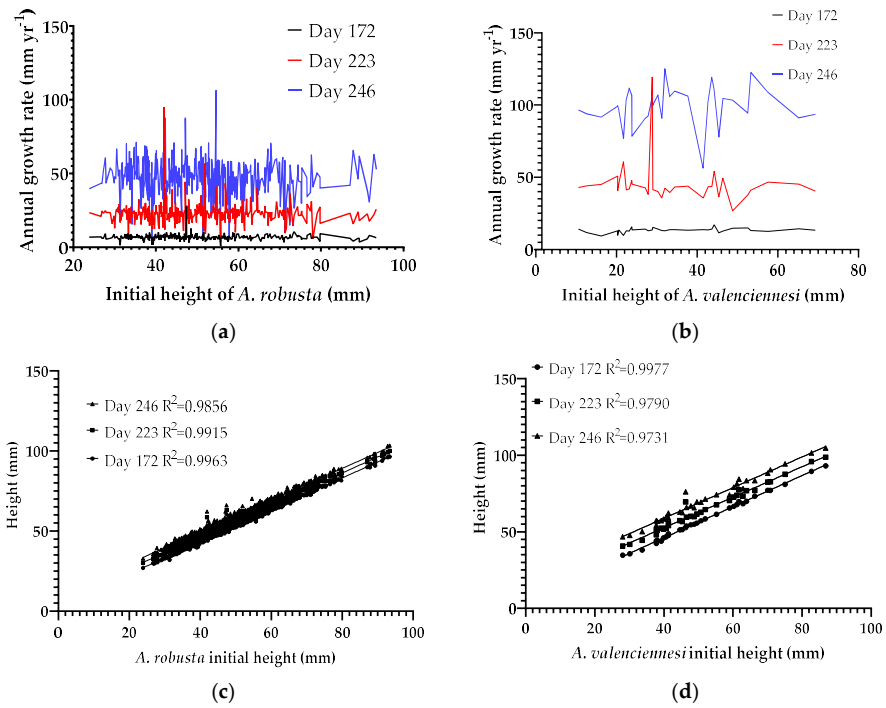


**Figure 5.** Effects of initial height of transplant at different time points: (**a**) changes in annual growth rate of transplants relative to initial height of *A. robusta* ($n$ = 414); (**b**) changes in annual growth rate of transplants relative to initial height of *A. valenciennesi* ($n$ = 33); (**c**) linear regression model for height changes against initial height in *A. robusta*; (**d**) linear regression model for height changes against initial height in *A. valenciennesi*.

### *3.6. Growth of Coral Fragments in Individual Plugs*

Coral fragments that were transplanted using individual plugs showed good growth regardless of species (Figure 6a). However, the rate of growth significantly decreased over time, more so for *A. robusta*. The annual growth rate declined from 14.86 ± 5.450 to 7.916 ± 1.517 μmd$^{-1}$, and 25.48 ± 7.560 to 14.31 ± 1.986 mm yr$^{-1}$ for *A. robusta* and *A. valenciennesi*, respectively (Figure 6b).

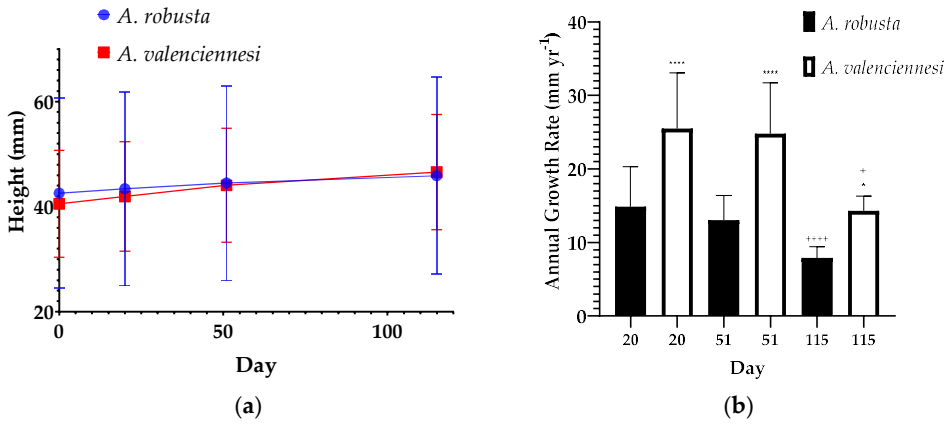


**Figure 6.** The growth of coral transplanted using individual plugs: (**a**) the relative growth achieved at certain measured timepoints; (**b**) the daily growth rate between measured timepoints. * and **** denote statistical significance between species of same period at $p > 0.05$ and $p > 0.0001$ respectively, + and ++++ denote statistical significance between days of same species $p > 0.05$ and $p > 0.0001$ respectively.

### *3.7. Estimation of Financial Cost*

The establishment of a grid nursery from assembly to anchorage took about 20–30 min. A crew of 8 people (2 researchers as lead divers, 2 divers as assistants, 4 trained manual labor for assembly of nurseries on-board) could establish about 10 nurseries in 150 min, which would translate into approximately 30 nurseries per day at 8 working hours. Thus, the outplanting rate would be equivalent to 30 transplant $h^{-1}$ $person^{-1}$. The total financial cost is shown in Table 2 and is prorated as USD 2.50 per coral for 246 days (~8 months).

**Table 2.** Cost estimation for construction of 30 coral nurseries with 64 propagation plugs each.

| Description | Cost/Unit (USD) | Quantity | Total (USD) |
|---|---|---|---|
| 1 m of perforated 304-grade flat stainless-steel bar | 4 | 240 | 960 |
| Stainless steel propagation plug | 0.3 | 1920 | 576 |
| 1 m of perforated 304-grade L-shaped stainless-steel bar | 5.8 | 240 | 1392 |
| Nuts, bolts and screws | 0.02 | 3000 | 60 |
| Adhesive | 50 | 1 | 50 |
| Researcher | 120 | 2 | 240 |
| Diver | 170 | 2 | 340 |
| Boat crew | 65 | 2 | 130 |
| Trained manual labor/graduate students | 35 | 4 | 140 |
| Boat rental | 800 | 1 | 800 |
| Dive equipment | 20 | 2 | 40 |
| Food | 5 | 16 | 80 |
| | | Total (USD) | 4808 |

## 4. Discussion

Large-scale coral gardening has been successfully carried out in various reef restoration programs. However, the practice has numerous challenges in terms of financial feasibility. This is particularly true for coral gardening using sexual propagation, which requires a substantial period of time to allow for spawning, fertilization, larvae settlement, and other stages before reaching a suitable size for transplantation. These extra phases not only add to the length and cost of coral gardening but also lead to a reduced number viable corals for outplanting due to high post-settlement mortality [20]. Moreover, many coral gardening programs require ex situ nurseries, which can be challenging when the restoration target lies in remote areas. On the other hand, while direct transplantation provides a cheap way to restore reefs, they often are perceived to produce unreliable results due to high mortality rate [17,23,26,29]. Nevertheless, some studies indicate that inclusion of ex situ nurseries is not necessary to achieve acceptable coral survival or growth after outplanting [30–33], which is also supported by our results (Table 1).

Micro-fragmenting has emerged as a powerful tool in reef restoration [16,26,33]. The technique usually refers to creation ~1 $cm^2$ of fragments and is frequently used in coral restoration programs. Among coral genera that has been outplanted using micro-fragmentation are *Orbicella*, *Montastrea* [32], *Montipora*, *Porites* [13,16], *Acropora* and *Merulina* [13]. In this study, we used a hybrid approach of building in situ coral nurseries on restoration sites via direct transplantation of coral fragments. The survival rate (Table 1) after 246 days post-transplantation is 94.58%, which is comparable to other studies [33,34] within a similar period. The corals adapted well to our method, growing consistently (Figure 2), with no signs of bleaching for the two species involved. Nevertheless, the fixation of transplant to the propagation plugs in our study needs to be improved as strong currents caused 24 transplanted corals to be detached from the plugs (Table 1).

Although both species were successfully fragmented and transplanted, our data suggests that *A. valenciennesi* exhibited a significantly higher post-transplantation growth rate than *A. robusta* (Figure 4), which could be due to the different growth morphology of each species [35]. Similarly, *A. valenciennesi* also performed better when the species were outplanted individually (Figure 6). Even though both species showed reduced growth rate over time (Figure 6b), *A. robusta* experienced a significantly larger decline compared to *A. valenciennesi*. The variation in growth rates observed in our study aligns with previous research, which reported the growth rates of *A. robusta* and *A. valenciennesi* as 57.6 mm $yr^{-1}$ [36] and 71–333 mm $yr^{-1}$ [37], respectively. Since the annual growth rates recorded in this study continue to rise (Figure 4), it is possible that even greater differences exist between the two species, as the ratio of their relative growth increased from 1.95 (day 172) to 2.08 (day 246). This may be due to *A. valenciennesi* devoting more energy on linear extension compared to *A. robusta*. Interestingly, the annual growth rate for both species seems to be increasing at a factor of 2–3.5 across each measured timepoints during study period (Figure 4), cumulating in a final 6.96 and 7.46, respectively, for *A. robusta* and *A. valenciennesi*. Given that the outplanting stage for the grid nurseries was performed on 7 November 2023, this phenomenon may be attributed to a combination of elevated sea surface temperature (approximate mean of 27.7 °C) and increased water clarity [38,39] during the later stages of the experiment (June to July), which likely enhanced the photosynthetic activity of zooxanthellae and, consequently, promoted coral growth. It is also possible that after a period of acclimatization, the *Acropora* spp. are starting to show their natural growth dynamics, given that the final achieved annual growth rate in our study (47.6 mm $yr^{-1}$ and 99.19 mm $yr^{-1}$, respectively, for *A. robusta* and *A. valenciennesi*) is still below what was reported by other studies [36,37]. Furthermore, as the corals grow, they theoretically have more tissues contributing to growth, resulting in the exponential growth observed in Figure 3.

The effect of fragment size on the growth of outplanted corals is not clearly established, with reports suggesting an inverse, neutral, or positive relationship [16,32,33,40–43]. For instance, Page et al. and Yeemin et al. compared the growth rate of coral fragments of different sizes and found that smaller fragments would generally outgrow larger fragments, at least in the initial stages of outplanting [32,33], whereas Forsman et al. [42] found that larger fragments grow faster. For our study, Pearson correlation analysis indicates that the annual growth rate of both *Acropora* species is generally independent of the initial size of the fragment. However, there is a weak but statistically significant negative correlation on day 246 for *A. robusta* (Figure 5a). Linear regression modeling further revealed that the post-transplantation changes in height of our coral fragments follow a linear regression model throughout the study period when plotted against the initial height of the outplant (Figure 5c,d). This suggests that both species experienced constant absolute growth rates regardless of initial size. However, it is also possible that statistical significance could not be reached due to the limited timeframe (in the case of *A. robusta*) or sample size (in the case of *A. valenciennesi*). Given that the $R^2$ values for both corals gradually deviate from 1 in the regression growth model over time, more research is needed to determine the post-transplantation growth dynamics of *Acropora* spp. in response to initial fragment size.

Even though fragment size of the outplant is considered critical to the survival of transplanted corals [44], findings from Knopp et al. suggested that size does not necessarily dictate survivorship and growth in the field, especially when there is lack of coral predation in the restoration site [16], similar to our study (Table 1, Figure 5). Therefore, it is essential to determine the optimal fragment size to maximize both survival and growth rates, which ultimately enhances the success of coral gardening in reef restoration efforts. Consequently, future studies in this project will focus on developing species-specific growth models

for fragmented corals, providing a more comprehensive understanding of the impact of fragmentation on different coral species. Additionally, future observations based on the current restoration project will employ 3D photogrammetry [45] to measure total surface area of corals instead of height, as this method offers a more accurate growth metric by eliminating growth morphology as a confounding factor [46].

Interestingly, our data showed that the corals transplanted using grid nurseries experience increasing annual growth rates as opposed to a decreasing annual growth rate for corals transplanted in individual plugs (Figure 6b). The observed trend is in contrast to the findings by Lirman et al., who reported that *Acropora palmata* has higher growth and productivity at lower outplanting density due to higher availability of resources. Given that the period of individual outplanting is within the period of grid nurseries outplanting, the discrepancy could be driven by non-climate factors such as predation [47].

One of the critical determinants for a successful active coral restoration program is the investment needed, including personnel and time. A coral transplantation project by Guest et al. reported that the successful transplantation of sexually propagated corals from an in situ coral nursery cost USD 61–284 per coral after 2.5 years, depending on the age and size of the outplant, which significantly influences the post-transplantation survival rate [20]. In contrast, the economic cost in our study is significantly lower, amounting to just USD 2.50 per coral after approximately 8 months (Table 2). Assuming that the survivorship of the outplants remains constant, the figure reached in our study is also lower than the USD 4.00 per coral reported by Tortolero-Langarica et al. [26] after 13 months, who similarly bypassed the use of an intermediate coral nursery. Moreover, the cost calculation by Tortolero-Langarica et al. excluded certain indirect costs such as food supplies and scuba gear costs, which are included in our estimation. The transplantation rate achieved in our study (30 transplant $h^{-1}$ $person^{-1}$) is also superior than what was achieved in that study (5 transplant $h^{-1}$ $person^{-1}$). In addition, the detachable design of the grid assay used in this study allows for quick adaptation to different site topographies with no notable compromise in growth (Figure 5). The assembled coral nursery, secured via four V-shaped angle steel bars, exhibits adaptability to a range of substrate types (Figure 1). This versatility is particularly salient, given that substrate instability is frequently cited as a primary factor contributing to the failure of coral reef restoration initiatives [48]. The combination of cost-effectiveness and time efficiency makes this method particularly suitable for restoring reefs in areas frequently impacted by natural disturbances such as tropical storms and hurricanes.

From an ecological perspective, this study employed a plastic-free approach, eliminating the need for cable ties and other plastic materials commonly used in restoration projects [34,35]. The use of plastic materials in conservation is less then desirable, since it would inevitably contribute to micro-plastic pollution in the ocean [27], and subsequently threatens the very coral reef ecosystem that was to be restored [49]. Over time, the coral outplants and the steel structure would be integrated into the reef ecosystem. The stainless-steel grids and plugs would eventually be partially or fully covered by coral and other marine organisms, becoming a permanent part of the reef structure. During this period, the corals may become attached to the surrounding substrate or other corals as the stainless-steel structure disintegrates. Moreover, the calcified structures of the corals themselves can provide a stable base for continued growth, even as the original steel support becomes less intact. In addition, the sturdier stainless-steel plugs used in this study are more suitable for the local climate compared to brittle materials such as ceramics and terracotta tiles, as Boundary Island experiences annual typhoons. Other materials such as limestone or bio-engineered materials are either costly or require technical knowledge that would be a barrier for restoration projects in developing countries [48]. Moreover, the iron content

in stainless steel may benefit Symbiodiniaceae growth [50], potentially enhancing their photosynthetic activity [51], which in turn promotes coral growth.

Finally, it is crucial to emphasize that while active restoration methods, like the one showcased in our study, can help to rescue and rehabilitate deteriorated reefs [52], these are short-term solutions and not a panacea for coral bleaching. The effectiveness of active restoration remains a topic of ongoing debate among coral conservationists, with significant concerns regarding the sustainability of coral gardening [53,54]. One major issue is that it does not address the root cause of coral bleaching. Thus, restored corals may still be vulnerable to future bleaching events, potentially rendering restoration efforts futile and wasting valuable resources. For example, while major restoration initiatives like NOAA's "Mission: Iconic Reefs" and Mars' "The Big Build" have successfully restored a significant number of corals [55,56], these corals remain at risk of future bleaching due to climate change. In addition, logistical capacity and scaling costs present additional challenges to the global application of active restoration methods like coral gardening. Ultimately, effective governance and policies aimed at mitigating climate change remain the most reliable approaches to preventing coral bleaching [18,57].

## 5. Conclusions

This study presents a cost-effective approach to establishing in situ coral nurseries through a combination of coral fragmentation and direct transplantation. Our method allows coral nurseries to be set up directly at restoration sites without significant impacts on coral survival or growth. By streamlining the process and minimizing resource use, we significantly reduced restoration costs, making it more feasible for regions facing coral bleaching crises. Further study is warranted to understand the different growth rate experienced by different species, and the optimal size for coral fragmentation.

## 6. Patents

The grid nursery design used in this study is patented by P.W. and Y.C.

**Author Contributions:** Conceptualization, P.W., A.W. and Y.C.; methodology, P.W., M.L. and L.Z.; software, M.L. and Y.C.; validation, M.L., D.L. and X.X.; formal analysis, M.L. and Y.C.; investigation, M.L. and L.Z.; resources, D.L., Y.C. and W.W.; data curation, Y.C. and P.W.; writing—original draft preparation, M.L. and Y.C.; writing—review and editing, Y.C.; visualization, L.Z., M.L. and Y.C.; supervision, A.W., P.W. and X.X.; funding acquisition, W.W., P.W., D.L. and X.X. All authors have read and agreed to the published version of the manuscript.

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