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The Influence of Oceanographic Factors on the Growth Rate of Transplanted *Acropora muricata* in Bone Bay, Indonesia

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ABSTRACT
This study examined the influence of oceanographic factors on the growth of transplanted *Acropora muricata* in Bone Bay, Indonesia, over a four-month monitoring period. Coral growth was measured at four stations positioned along a nearshore–offshore gradient, while key environmental parameters (temperature, salinity, light intensity, pH, dissolved oxygen, nitrate, and phosphate) were simultaneously assessed. Results indicated that growth increased steadily from November (8.48cm) to February (9.85cm), with significant spatial differences among stations ($P < 0.001$). Station 2 exhibited the highest mean growth (9.44cm), while Station 4, the farthest offshore, showed the lowest (8.78cm), suggesting that factors beyond distance from shore drive coral performance. Pearson correlation analysis revealed positive associations of growth with pH ($r = 0.54$) and phosphate ($r = 0.35$), and negative associations with nitrate ($r = –0.42$) and salinity ($r = –0.38$). Multiple regression explained 67% of growth variability ($R^2 = 0.673$), with phosphate emerging as the strongest positive predictor ($\beta = 0.60$, $P = 0.035$). Principal component analysis further demonstrated alignment of growth with phosphate, pH, and dissolved oxygen, while nitrate and temperature were oppositely loaded. These findings highlight that balanced nutrient availability and stable carbonate chemistry are essential for coral transplant success. The study emphasized the importance of considering local environmental conditions when selecting sites for reef restoration.

INTRODUCTION

Coral reefs are among the most biodiverse ecosystems on Earth, providing essential ecological services such as coastal protection, fisheries support, and carbon sequestration. However, they are increasingly threatened by anthropogenic pressures and global climate change. Over the past three decades, coral reef cover worldwide has declined drastically due to destructive fishing, eutrophication, sedimentation, and rising sea surface temperatures, which have triggered recurrent bleaching events **(Hughes *et al.*, 2017;**

Hughes *et al.*, 2018). These stressors have altered reef community structures and undermined their ecological resilience.

Indonesia, located at the heart of the Coral Triangle, hosts nearly 18% of the world's coral reefs, yet more than half are degraded, with many classified as being in poor to moderate condition **(Hadi *et al.*, 2018)**. Bone Bay, South Sulawesi, represents a critical habitat within this region but faces cumulative impacts from overfishing, aquaculture, terrestrial runoff, and coastal development **(Irwan *et al.*, 2018; Sampe, 2024)**. These pressures compromise reef resilience and hinder natural recovery processes.

In response, coral transplantation has emerged as one of the most widely applied restoration strategies in Indonesia and globally **(Okubo *et al.*, 2005; Veronika & Tajidan, 2022)**. Transplantation of branching corals such as *Acropora muricata* has shown promising results, with growth rates varying between 26 and 39mm/ month depending on species and location **(Hidayat, 2021; Utami, 2021)**. Nevertheless, transplantation success is not solely determined by the coral species or method used, but also by site-specific oceanographic conditions. Water quality parameters such as temperature, salinity, nutrient, dissolved oxygen (DO), and light penetration have been shown to directly affect coral physiology, calcification, and survival **(Martins *et al.*, 2022; Tagliafico *et al.*, 2022)**.

Despite the importance of these environmental drivers, studies focusing on how local oceanographic conditions influence transplantation outcomes in Bone Bay remain limited. Previous research in the region has mainly emphasized coral cover and fish assemblages **(Irwan *et al.*, 2018; Sampe, 2024)**, with little attention to the direct relationship between transplantation success and water quality. Addressing this knowledge gap is crucial for designing site-appropriate restoration strategies.

Therefore, this study investigated the influence of key oceanographic parameters on the growth rate of transplanted *A. muricata* in Bone Bay. Specifically, correlations between coral growth and water quality factors across multiple stations were examine, providing insights into the environmental constraints shaping reef rehabilitation efforts in this ecologically important area.

MATERIALS AND METHODS

The study was conducted over a period of four months in Bone Bay, specifically in coastal areas with coral reef ecosystems. Monthly observations were carried out at four pre-determined stations based on their distance from the coastline, assuming that differences in station distance from the coastline would influence variations in water conditions. This in line with the paradigm that waters farther from land and rivers will have clearer water **(Turner *et al.*, 2021; Irwan *et al.*, 2024)**. The observation stations at the research location are shown in Fig. (1).

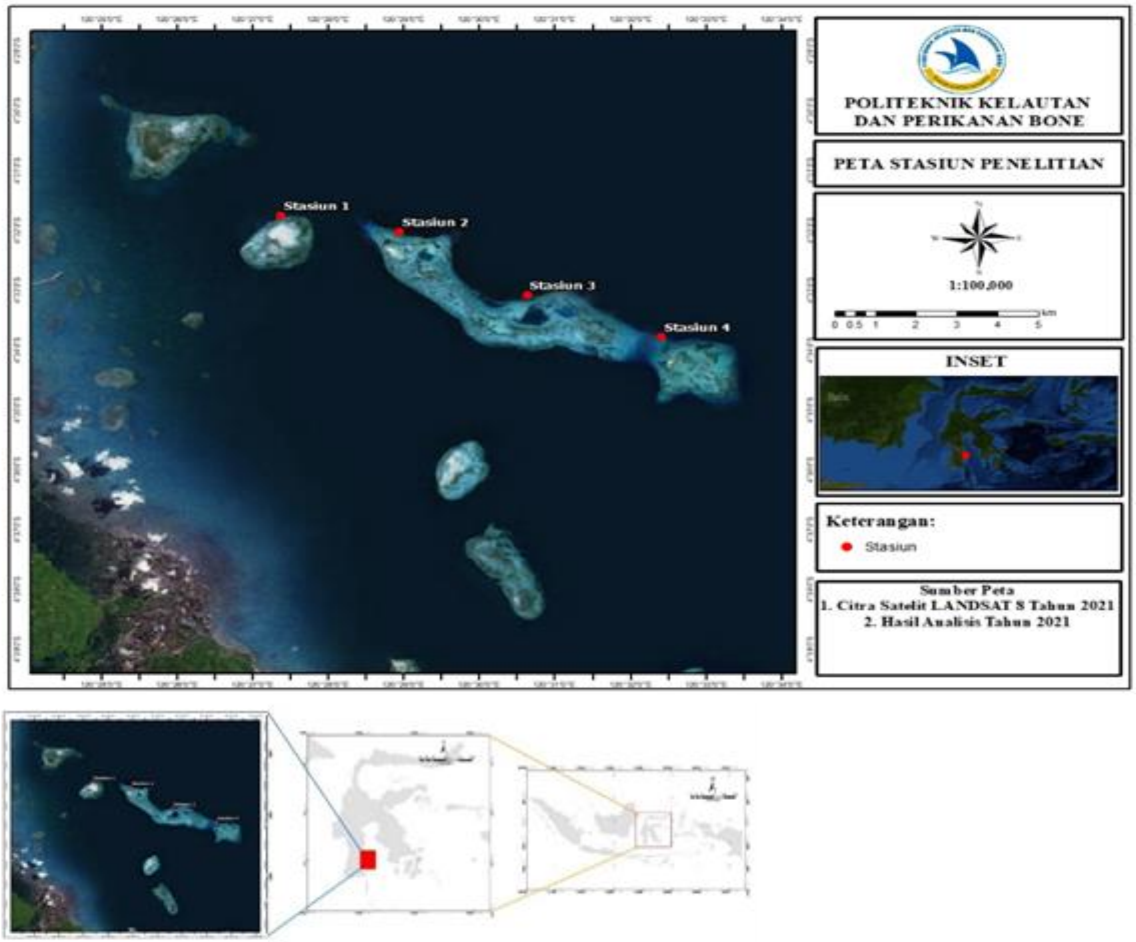

Fig. 1. The research location with 4 station in Bone Bay

The study was conducted over a four-month period in Bone Bay, South Sulawesi, with its underlying coral reef ecosystem. Monthly observations were carried out at four stations located at varying distances from shore. At each station, five transplantation tables were installed at a depth of 3m. Each table contained 10 fragments of branching coral *A. muricata* (Linnaeus, 1758), as shown in Fig. (2).

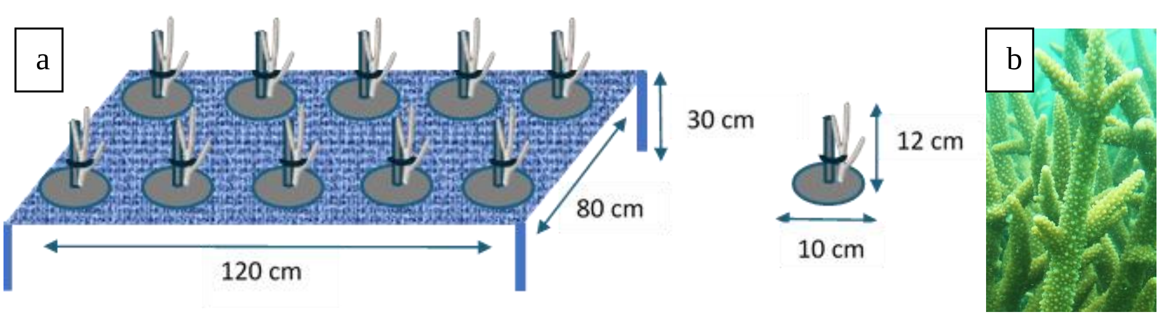

Fig. 2. Illustration of a transplantation table with 10 coral fragments attached to a pole using cable ties (a) and *A. muricata* coral as the object of observation (b)

Coral growth and water quality parameters were monitored monthly. Water quality parameters included temperature, salinity, nitrate, phosphate, pH, dissolved oxygen (DO), and water transparency (using a Secchi disk). Nutrient concentrations were analyzed in the laboratory using spectrophotometry.

The growth data of *A. muricata* and oceanographic parameters were analyzed descriptively. The relationship between oceanographic factors and coral growth was analyzed using heatmap correlation, ANOVA and the model was analyzed using multiple linear regression. The influence of oceanographic factors was analyzed using principal component analysis (PCA). All statistical analyses were completed using R Studio.

RESULTS

1. Oceanographic parameters

Descriptive analysis of water-quality parameters across the four monitoring stations revealed relatively stable conditions throughout the study period. Mean seawater temperature ranged between 30.5–31.8°C, with slightly higher values recorded at offshore stations (Stations 3 and 4). Salinity varied narrowly (30.1– 31.6ppm), but the lowest values were observed at Station 3, while Station 1, closest to shore, exhibited relatively higher salinity. Light intensity increased gradually with distance from shore, ranging from an average of 10.25m at Station 1 to 14.44m at Station 4, reflecting improved water transparency offshore. Mean pH was slightly alkaline (7.90–8.16) with little variation among stations, while dissolved oxygen (DO) ranged from 4.0 to 5.9mg L^{-1}, highest at Station 3. Nutrient concentrations were low overall: nitrate values were 0.01– 0.03mg L^{-1}, with slightly elevated levels at Station 3, while phosphate remained between 0.01– 0.02mg L^{-1}, with marginally higher values at Station 4. These observations suggest that spatial gradients exist, particularly for light intensity, DO, and nutrients, which may influence coral growth.

2. Coral growth

The growth of transplanted *A. muricata* exhibited clear spatial and temporal variability. Mean colony size increased steadily across the four-month period, from 8.48cm in November to 9.85cm in February, indicating positive net growth during the monitoring period. Spatially, Station 2 recorded the highest average growth (9.44cm), while Station 4, the farthest from shore, showed the lowest (8.78cm). These values are comparable to growth rates reported in other transplantation studies in Indonesia **(Rizqika *et al.*, 2018; Hariyanto *et al.*, 2023; Kati *et al.*, 2023)**, though lower than those observed in nutrient-rich but stable environments such as Paiton, East Java **(Khasanah *et al.*, 2020)**. Interestingly, growth did not follow a simple nearshore–offshore gradient, as intermediate stations demonstrated higher performance than the outermost site. This suggests that multiple interacting factors, rather than distance from shore alone, govern coral transplant performance.

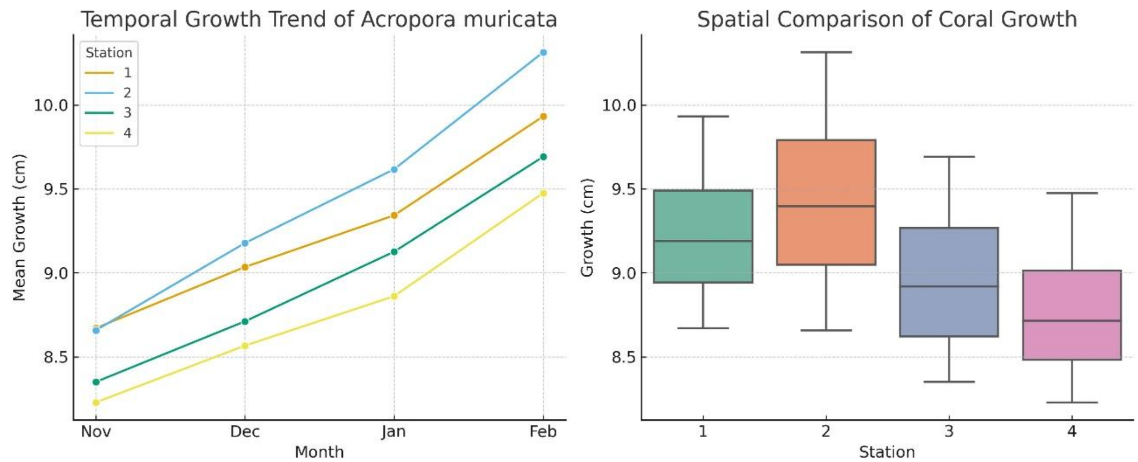

Fig. 3. Temporal and spatial variation in coral growth. (A) Mean growth of transplanted *A. muricata* (cm) observed across four months (November–February) at four monitoring stations. (B) Boxplots showing spatial differences in growth among stations (Station 1 nearest to shore; Station 4 farthest offshore). Growth increased consistently over time, while Station 2 showed the highest overall mean growth

3. Relationship with oceanographic factors

Preliminary analyses revealed clear spatial and temporal trends in the growth of transplanted *A. muricata*. Over the four months monitored (November–February), mean growth increased steadily from approximately 8.48 to 9.85cm. Spatially, Station 2 (intermediate distance from shore) exhibited the highest average growth (~ 9.44cm), while Station 4 (farthest offshore) displayed the lowest (~ 8.78cm). A two-way ANOVA confirmed that both sampling station ($P < 0.001$) and month ($P < 0.001$) had significant effects on coral growth.

Pearson correlation analysis showed that coral growth was positively correlated with pH ($r = 0.54$) and phosphate ($r = 0.35$), while negatively correlated with nitrate ($r = –0.42$) and salinity ($r = –0.38$). Temperature also showed a weak negative association ($r = –0.22$), whereas light intensity had a weak positive relationship ($r = 0.19$). Dissolved oxygen exhibited no meaningful relationship with growth ($r \approx 0.00$). These correlations suggest that coral growth was favored by more alkaline conditions and moderate phosphate levels, while elevated nitrate and salinity appeared to inhibit growth (Fig. 4).

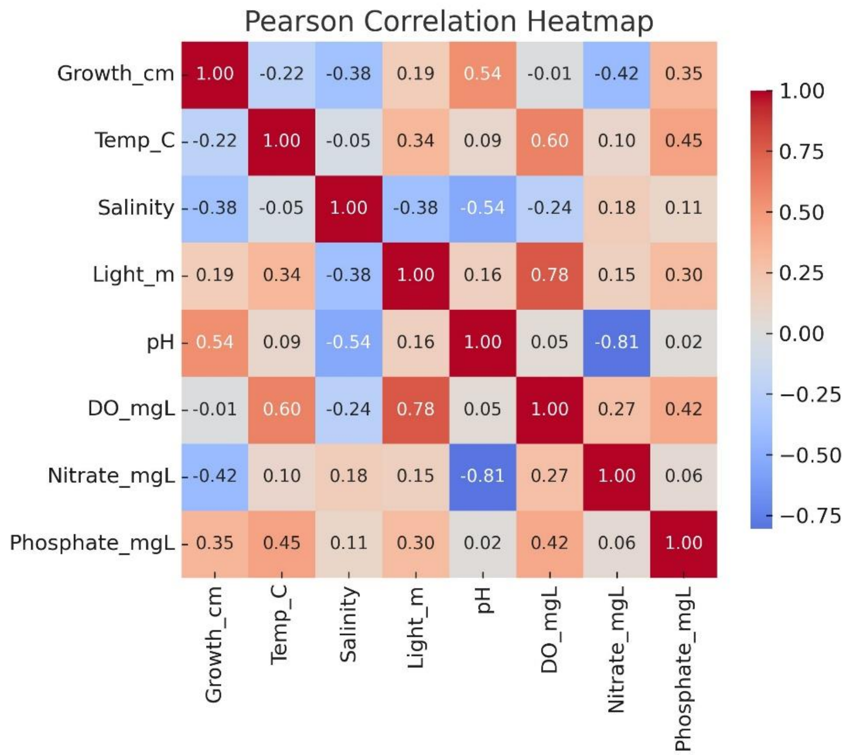

Fig. 4. Pearson correlation heatmap between coral growth and water-quality parameters. Correlation coefficients (r) are shown for growth and seven environmental variables. Warm colors represent positive correlations, cool colors indicate negative correlations. Coral growth was positively correlated with pH and phosphate, and negatively correlated with nitrate and salinity

A multiple regression model incorporating all measured water-quality variables explained 67.3% of the variance in coral growth ($R^2 = 0.673$), though model significance was constrained by the small sample size and high collinearity among predictors. Standardized coefficients identified phosphate as the strongest positive predictor ($\beta = 0.60$, $p = 0.035$), while temperature ($\beta = -0.52$, $P = 0.10$) and pH ($\beta = 0.51$, $P = 0.34$) also showed substantial but non-significant effects. Other variables (salinity, light, DO, nitrate) were not significant in the multivariate model. Variance Inflation Factor (VIF) values were extremely high, confirming multicollinearity among predictors, which reduces the interpretability of individual coefficients. Nonetheless, phosphate consistently emerged as the most influential factor supporting coral growth.

PCA revealed that the first two principal components (PC1 and PC2) together explained 63% of the total variance. PC1 (33%) was primarily structured by positive loadings of pH and dissolved oxygen, opposed by temperature. PC2 (30%) was dominated by phosphate (positive) and nitrate (negative). Coral growth loaded strongly along the same axis as phosphate and, to a lesser extent, pH and dissolved oxygen, while opposing nitrate and temperature. This confirms the regression and correlation findings that phosphate availability and stable carbonate chemistry (higher pH) are favorable to coral growth, whereas nitrate enrichment and elevated temperature may act as stressors (Fig. 5).

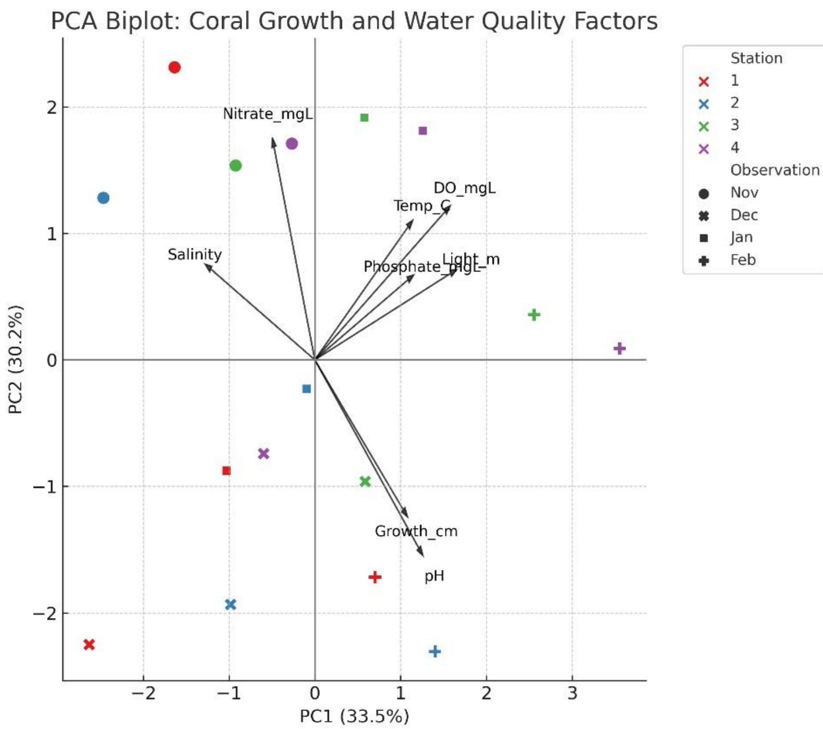

Fig. 5. Principal Component Analysis (PCA) biplot of coral growth and water-quality variables. Scores represent individual observations, differentiated by station (color) and month (marker style). Arrows indicate loadings of growth and environmental variables on PC1 and PC2, which together explained 63% of variance. Coral growth aligned closely with phosphate, and to a lesser extent with pH and dissolved oxygen, while nitrate and temperature loaded in the opposite direction

DISCUSSION

a) Spatial and temporal influences on coral growth

The results demonstrated that both spatial and temporal factors significantly affected the growth of *A. muricata*. Growth increased steadily from November to February, reflecting seasonal improvements in water quality, such as stable temperature and nutrient availability. This trend corroborates findings by **Cantin *et al.* (2010)**, who reported that ocean warming and seasonal variability strongly modulate coral calcification. Our ANOVA confirmed that both month and station effects were highly significant ($P < 0.001$), underscoring the influence of environmental dynamics at multiple scales. Notably, Station 2 exhibited the highest growth despite not being the farthest offshore, indicating that optimal performance does not follow a simple distance-from-shore gradient but rather reflects the interplay of light availability, hydrodynamics, and nutrient balance.

Spatial variability among stations further suggests that site-specific factors strongly modulate transplant success. Station 4, despite experiencing the highest light penetration, recorded the lowest growth, possibly due to elevated temperature and reduced nutrient balance highlighting the complexity of coral environment interactions. Similar results were reported by **Anthony and Fabricius (2000)**, who showed that coral performance does not always peak in the clearest waters but in moderately turbid environments where nutrient inputs and light are optimally balanced. Therefore, restoration success depends not solely on distance from terrestrial influences but also on fine-scale variability in local environmental conditions.

b) Oceanographic factors influencing coral growth

Correlation and regression analyses identified phosphate as the dominant factor positively associated with coral growth, whereas nitrate and temperature exerted negative influences. The positive role of phosphate supports the view of **Rosset *et al.* (2017)**, who demonstrated that phosphate deficiency destabilizes coral–algal symbiosis and promotes bleaching, while adequate phosphate availability sustains holobiont functioning. Our regression analysis confirmed phosphate as a significant predictor ($\beta = 0.60$, $P = 0.035$), underscoring its critical role in maintaining transplant growth in oligotrophic tropical waters. The positive correlation with pH further highlights the importance of carbonate chemistry, consistent with **Mollica *et al.* (2018)**, who found that low pH reduces skeletal density in corals as a consequence of ocean acidification.

In contrast, elevated nitrate levels were negatively associated with coral growth. This result aligns with **Marangoni *et al.* (2020)**, who demonstrated that nitrate enrichment disrupts redox homeostasis and increases bleaching susceptibility under thermal stress. Similarly, **Hughes *et al.* (2017)** reported that nutrient enrichment can exacerbate coral vulnerability to heat stress, thereby reducing resilience. The weak but negative influence of temperature in our dataset also supports global evidence that thermal stress impairs coral calcification **(Cantin *et al.*, 2010)**. Together, PCA results reinforced that coral growth aligned with phosphate, pH, and dissolved oxygen, while opposing nitrate and temperature. Importantly, these findings emphasize the synergistic role of nutrient balance and stable carbonate chemistry in supporting coral transplant resilience under environmental stressors.

This study provides new evidence that coral transplant performance is governed not solely by distance from shore but by the interaction of multiple oceanographic drivers, particularly nutrient balance and carbonate chemistry. The finding that phosphate availability enhances growth while nitrate enrichment and elevated temperature suppress it is consistent with broader ecological theory on coral nutrient limitation **(Wiedenmann *et al.*, 2013; Ferrier-Pagès *et al.*, 2016)**. Moreover, the positive role of pH emphasizes the vulnerability of reef-building corals to ocean acidification, which reduces calcification and skeletal density **(Pandolfi *et al.*, 2011; Cornwall *et al.*, 2019)**. By combining ANOVA, regression, and PCA, this research delivers a robust analytical framework that can be applied to other reef systems to identify optimal restoration sites.

From a management perspective, the results highlight that restoration strategies should prioritize sites with stable carbonate chemistry and balanced nutrient regimes rather than simply targeting offshore locations with clearer water. Similar recommendations have been made in other reef systems, where site selection incorporating water quality monitoring improved survival and growth outcomes of transplants **(Edwards & Gomez, 2007; Ng *et al.*, 2020)**. In this sense, the present study contributes to advancing evidence-based reef restoration in Indonesia, providing both regional baseline data for Bone Bay and broader guidance for tropical coral reefs under climate change pressures. The novelty of this work lies in demonstrating the synergistic influence of phosphate, nitrate, temperature, and pH on transplanted coral growth and translating these ecological insights into practical recommendations for reef management and conservation.

CONCLUSION

This study demonstrates that both spatial and temporal variability significantly influence the growth of transplanted *A. muricata* in Bone Bay. Coral growth increased progressively over time, with Station 2 showing the highest performance, indicating that local conditions—beyond simple distance from shore—play a critical role in transplant success.

Among the oceanographic parameters, phosphate emerged as the most important positive driver of growth, while nitrate and temperature were identified as limiting factors. The positive association with pH underscores the importance of stable carbonate chemistry in supporting calcification. Multivariate analyses (ANOVA, regression, PCA) consistently revealed that coral performance is governed by a delicate balance of nutrient availability and physicochemical stability.

These findings emphasize that successful coral reef restoration requires careful consideration of site-specific environmental conditions, particularly nutrient dynamics and water chemistry. Maintaining oligotrophic but phosphate-adequate environments may enhance the resilience and growth of coral transplants. Future long-term studies with larger datasets are needed to strengthen these conclusions and inform adaptive management strategies for coral reef restoration under ongoing climate change.

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