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Ecological Impact of Coral Reef Restoration Through Transplantation Following Bleaching Events in Liukang Loe Island, Indonesia

Ahmad Faizal*, Chair Rani, Abdul Haris, and Rachamt Hidayat
Department of Marine Science, Faculty of Marine Science and Fisheries, Universitas Hasanuddin, 90245, Makassar, Indonesia

***Corresponding Author : ahmad.faizal@unhas.ac.id**

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ABSTRACT

Efforts to rehabilitate coral reefs affected by the 2016 bleaching event were undertaken in 2019 using transplantation techniques. These techniques involved attaching coral fragments to various types of intact dead coral substrates. This study aimed to analyze the ecological impacts of the 2019 rehabilitation efforts by examining changes in live coral and algae cover, as well as the species richness and abundance of benthic organisms and associated reef fish within the transplant area. Observations of live coral and algae cover were conducted using a 0.5 × 0.5 m² quadrat divided into 25 grids of 10 × 10 cm². Species and abundance data for benthic organisms and reef fish were collected through visual census techniques within a 2 × 2 m² area, recording the species and the number of individuals observed. These observations were conducted once during the five-month observation period. The study assessed the dynamics of live coral and algae cover, along with species richness and abundance of benthic organisms and reef fish, by comparing ecological parameters across several substrate types, including non-transplanted areas used as controls (damaged corals dominated by rubble and natural corals). Statistical analysis of variance (ANOVA) was employed to evaluate these differences. The results indicated that the use of branching, massive, and tabulate dead coral substrates in transplantation generally had a positive impact, reflected by an increase in live coral cover and enhanced richness and abundance of reef fish. Notably, during July observations, massive dead coral substrates supported more species and a greater abundance of reef fish compared to the non-transplanted control (natural coral). Furthermore, the benthic community also benefited from the use of massive and tabulate substrates, as these attracted more benthic species and individuals to the transplant area compared to other substrate types.

INTRODUCTION

According to assessments by international institutions on climate change **(Mann & Kump, 2009)**, the consequences of climate change in coastal areas include an increase in sea surface temperatures by 1 to 3°C. This rise causes coral stress, ultimately leading to coral bleaching, mortality, and damage to coral reefs.

Reef-building corals exhibit a pronounced sensitivity to temperature fluctuations, with even minor increases beyond their thermal tolerance thresholds resulting in coral bleaching and mortality **(Hoegh-Guldberg, 1999)**. This vulnerability is further intensified by global climate change, which has led to a notable increase in sea temperatures over the past century **(Hoegh-Guldberg, 2000)**. Coral bleaching, predominantly induced by the expulsion of symbiotic algae due to thermal stress, constitutes a significant threat to coral ecosystems globally **(DeCarlo *et al.*, 2019)**. The prevailing trajectory of climate change indicates that corals are likely to encounter their thermal limits with greater frequency, resulting in more frequent bleaching events unless they can adapt or acclimate to these environmental changes **(Naugle *et al.*, 2024)**.

The effects of El Niño are particularly severe in reef areas. For example, 97% of corals in the Galapagos Islands died during an El Niño event. Similarly, 75–85% of corals along the coast of Panama and 58% in Costa Rica perished. A significant decline in live coral cover occurred in early to mid-2016. Coral bleaching began in the western Indian Ocean in January, peaking in May, with bleaching rates in Seychelles ranging from 69–99%, reducing hard coral cover by 50%. In Southeast Asia, coral bleaching led to the closure of many coral reefs in Thailand for diving activities **(Coral Reef Watch, 2018)**. Permanent monitoring sites reported an average decline of 68% in live coral cover, significantly reducing habitat complexity **(Couch *et al.*, 2017)**.

According to the World Meteorological Organization (WMO), 2015–2016 was the hottest period in the recorded history due to the El Niño phenomenon. During this period, the Earth's average surface temperature rose by about 1 °C compared to the pre-industrial era (1880–1899) and about 0.73°C above the 1961–1990 average. The El Niño event contributed approximately 16–20% of this increase. The 2016 El Niño is considered one of the strongest on record **(Viva News, 2016)**. Alongside the rise in global temperature, water temperatures in the Makassar Strait and Flores Sea increased from an average of 27 to 30°C, representing a 3°C anomaly **(Nirwan *et al.*, 2017)**.

Liukangloe Island, located in Bulukumba Regency in the Flores Sea, was also affected. Investigations by MSDC, Unhas, in March 2016, reported coral bleaching exceeding 50%, resulting in coral damage of over 40% **(Nirwan *et al.*, 2017)**. Further monitoring in 2017 found that bleaching was severe at a depth of 3–5 meters across all observation points, with coral mortality rates ranging from 35–60% **(Rani *et al.*, 2017)**. Coral reef degradation significantly alters the biophysical structure of reefs, leading to decreased spatial complexity, which impacts associated biota, particularly in terms of community structure as a response to habitat degradation.

In 2019, research was conducted on transplantation techniques using dead coral substrates unaffected by bleaching as attachment media to aid recovery. The results showed no significant differences in the growth of transplanted coral fragments across different substrate types, including natural coral controls. The study included three coral species: *Acropora nobilis*, *Acropora formosa*, and *Porites cylindrica* **(Rani *et al.*, 2020)**.

A comprehensive study on the ecological impact of post-rehabilitation activities, particularly following the 2019 transplantation efforts, is urgently needed. The objectives include analyzing ecological dynamics in restored coral reef areas, focusing on coral cover, algae, reef fish diversity and abundance, and megabenthic fauna.

MATERIALS AND METHODS

1. Study area

The research was conducted in the coral reef area of Liukangloe Island, Bulukumba Regency, from May to September 2021. Three research stations, located on the North and East sides of the island, were selected (Fig. 1). The primary consideration for choosing these locations was that all three stations are popular diving sites for foreign tourists and had also experienced significant coral bleaching. At Station 1, three observation areas were established, while Stations 2 and 3 each had one observation area, totaling five observation areas overall. According to **Rani *et al.* (2017)**, the variation in the number of observation areas at each station was determined by the frequency of coral bleaching incidents occurring at depths of 3–5 meters. Three observation points were set up within each area, based on the type of substrate media used for coral transplantation.

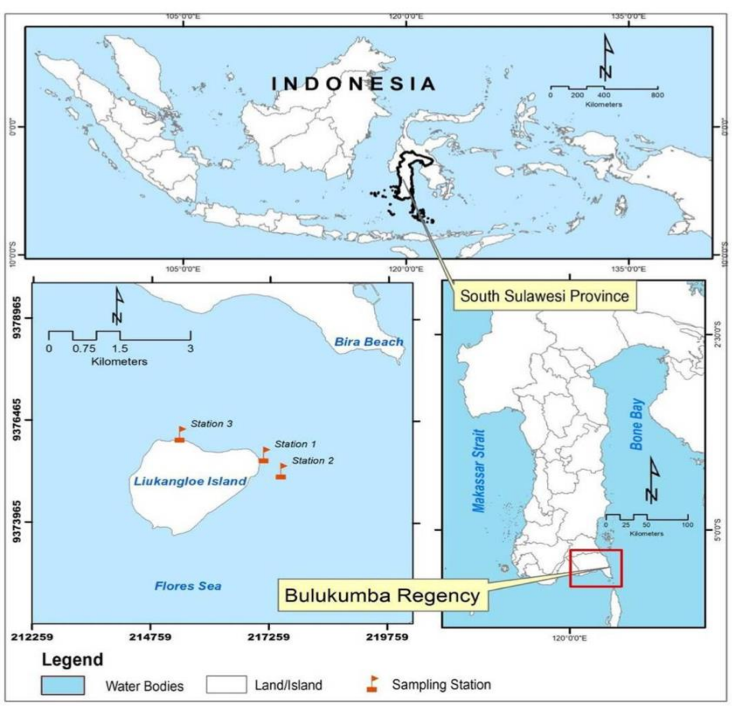

Fig. 1. The research location on Liukangloe Island, Bulukumba Regency

2. Data collection

The coral reef recovery technique utilized natural substrates composed of intact dead coral as a medium for coral attachment, specifically in massive, tabulate, and branching forms **(Rani *et al.*, 2020)**. Technically, the use of dead coral media as a substrate involved attaching 30 live coral fragments for each treatment type:

- **Branching dead coral**: Live coral fragments were tied to the natural substrate (dead coral branches) using cable ties.
- **Massive dead coral**: Coral fragments were attached to the natural substrate (dead massive coral) using concrete nails secured with plastic rope (cable ties), with a spacing of 20cm between fragments.
- **Tabulated dead coral**: Dead tabulate corals with large, intact branching structures were selected. Live coral fragments were tied to these branches using cable ties (Fig. 2).

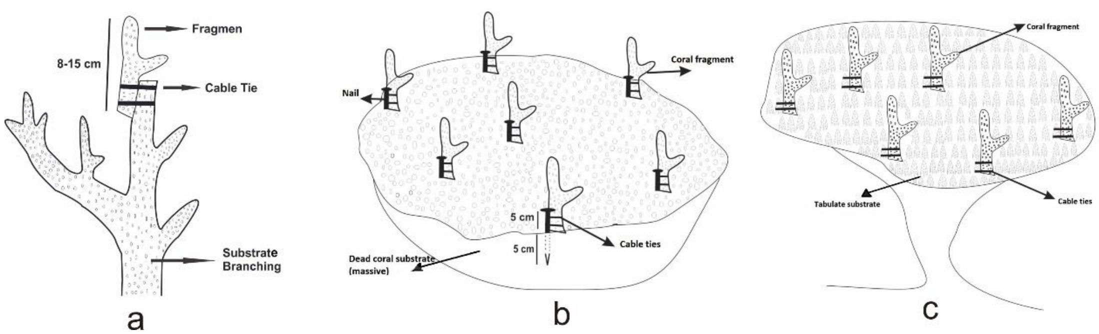

Fig. 2. Dead coral substrates used as media for coral fragment attachment in transplantation activities: (a) Dead coral branches; (b) Massive dead coral; and (c) Tabulated dead coral **(Rani *et al.*, 2020)**

Data collection procedure

- **Algal Cover**: Algal cover was assessed by placing a quadrant within the transplant area of each experimental unit using a dead coral substrate. The observation point was marked with a float to facilitate consistent quadrant placement. Algal cover percentage was measured using the modified method of **Faizal *et al.* (2011)**. A 0.5 × 0.5 m² quadrant with a 10 × 10 cm² lattice was used. Cover units within each lattice cell were categorized as ¼, ½, ¾, or 1 unit. The area of algal cover within the grid was recorded using these categories, and photographs were taken for documentation.

- **Reef Fish**: Observations of reef fish in each experimental unit were conducted using the Stationary Visual Census technique. Reef fish within a 2 m × 2 m (4 m^2) area were recorded for species and individual counts while the observer remained motionless at the center of the observation area. Reef fish identification followed the guidelines of **Allen (2000)**.
- **Control Areas**: Observations of reef fish and algal cover were also carried out in non-transplanted control areas, including damaged coral reef zones dominated by rubble and undisturbed natural coral areas. Observation areas matched the size of those in the transplanted zones (4 m^2) and were repeated five times.

Data analysis

The structure of the herbivorous reef fish community—defined as the proportion of herbivorous fish to the total number of reef fish (both species and individuals) within each substrate treatment and control area—was analyzed descriptively using graphical representations. Monthly variations in algal cover and herbivorous fish abundance were also examined and presented descriptively.

RESULTS

The fluctuations in live coral and algae cover, species diversity, and the abundance of benthic organisms and reef fish over the five-month observation period exhibited monthly variations between the transplantation and control media.

1. Live coral cover

The changes in live coral cover across different dead coral substrates and control areas over five months are illustrated in Fig. (3). Overall, live coral cover increased in all transplantation and control treatments throughout the observation period. Statistical analysis revealed a significant difference between the control and the three dead coral substrates used for transplantation. The highest live coral cover was recorded in the natural coral area (control), while the lowest was observed in the rubble coral control area. Live coral cover in the natural area was significantly higher than in the treated media and the rubble control area. However, there was no significant difference in live coral cover among the three dead coral substrate treatments.

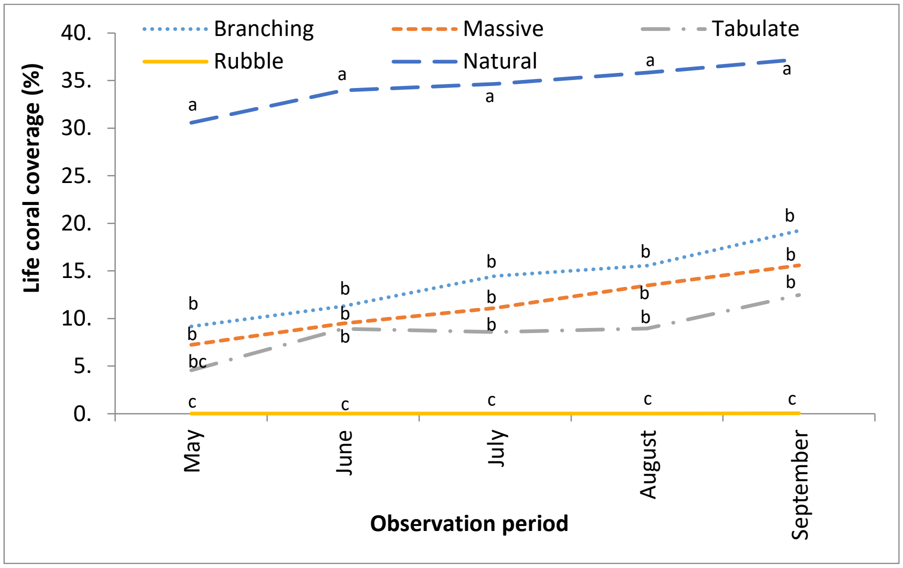

Fig. 3. The dynamics of live coral cover on various dead coral substrates as attachment media in coral transplantation for 5 months of observation

Different letters above the graph in each month of observation show a significant difference in alpha 5% based on the analysis of variance.

2. Algae cover

The study categorized algal cover dynamics into filamentous algae and coralline algae groups. Changes in algal cover over five months in the transplant area with different transplantation media are illustrated in Fig. (4). Significant variations were observed only in filamentous algae cover, while coralline algae cover remained relatively stable throughout the observation period.

Filamentous algae cover showed notable fluctuations in June and July, whereas in other months, variations were not significant. In June, high algal cover was recorded in branching media and rubble areas, differing from other media, including natural coral control areas. In July, tabulate dead coral substrates exhibited significantly higher algal cover compared to other substrates. Overall, algal cover declined at the start of the study across all media but increased toward the end, except in tabulate media. Meanwhile, coralline algae cover fluctuated significantly in June before stabilizing over the last three months of observation.

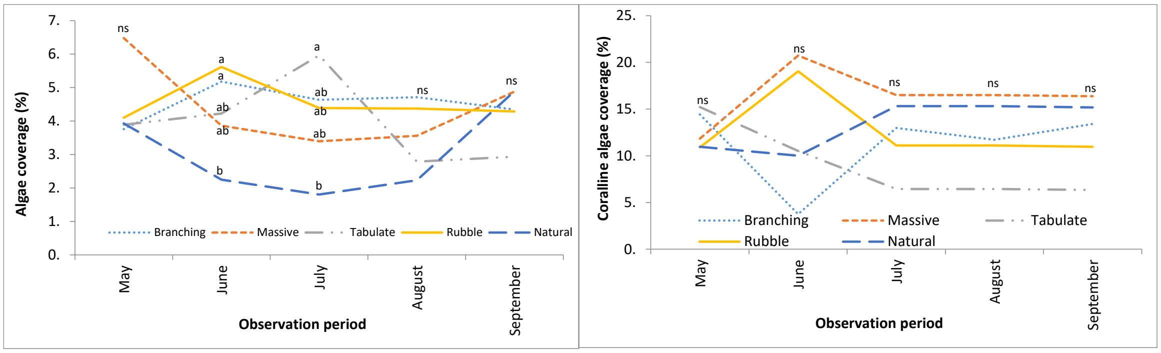

Fig. 4. The dynamics of algae cover (a) and coralline algae (b) on various dead coral substrates as attachment media in coral transplantation for 5 months of observation

Different letters above the graph in each month of observation show a significant difference in alpha 5% based on the results of the analysis of variance; ns: not significantly different.

3. Diversity and abundance of benthos

The species richness and abundance of benthic organisms increased over time across all substrates and control areas. However, variations were observed in the number of species and benthic abundance among different substrates, including the controls (Fig. 5). The use of massive and tabulated substrates attracted a greater diversity and number of benthic species in the transplant area compared to other substrates. Benthic species richness was lower on branching substrates, while benthic abundance was lower on branching substrates as well as in control areas (rubble and natural coral).

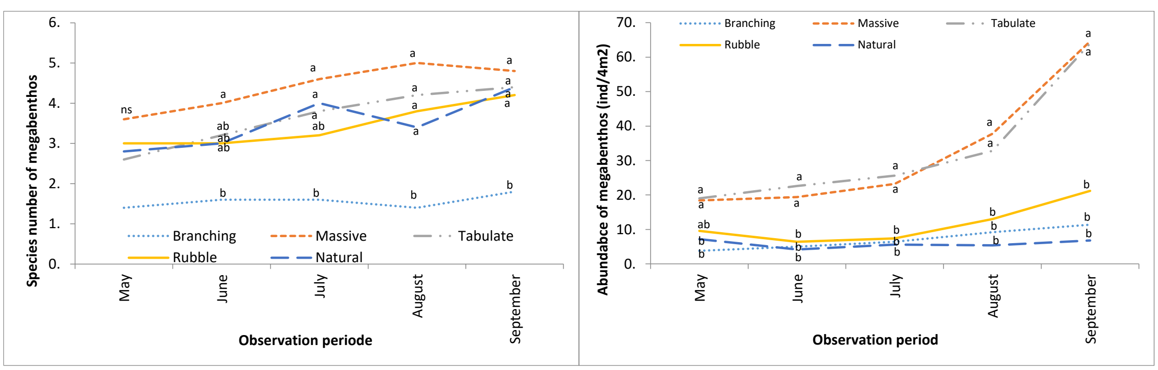

Fig. 5. The dynamics of species richness (a) and abundance of benthos (b) on various dead coral substrates as attachment media in coral transplantation for 5 months of observation

Different letters above the graph in each month of observation show a significant difference in alpha 5% based on the results of the analysis of variance; ns: not significantly different.

The abundance of benthic species and individuals on massive dead coral substrates is influenced by the large surface area of each colony, with some reaching up to a meter in diameter or more. Massive corals are typically spherical or boulder-shaped, providing a highly stable structure that resists damage from strong wave action. Their broad and stable surfaces offer ideal perching areas for benthic organisms, allowing them to forage and perform other biological activities. Similarly, tabulated dead coral substrates not only provide a wide surface but also contain gaps between their vertical branches, which may serve as shelter for small benthic organisms against strong currents.

The number and types of benthic species found on different dead coral substrates used as transplantation media, including controls, are summarized in Table (1). A total of 13 species from 5 different phyla were identified. The most abundant species observed was the tunicate *Didemnum molle*, which commonly inhabits coral reefs and forms colonies. Another frequently encountered species was *Fungia* spp., a solitary coral often found clustering in degraded reef areas. Additionally, the sponge *Rhabdastrella globostellata* was present across all transplantation and control substrates. Other notable species included the mollusk *Tridacna* spp. and the sea slug *Phyllidia varicosa*.

Table 1. Distribution of benthic species in various uses of transplantation media in the form of dead coral substrate

Phylum	**Megabenthos**	**Abundance (ind/4m^2)**				
		Branching	**Massive**	**Tabulate**	**Rubble**	**Natural**
Chordata	1. *Didemnum molle*	64	569	554	132	41
	2. Polycarpa aurata	0	28	11	9	5
Echinodermata	*3. Ophiuroidea brevispinum*	3	5	2	33	14
Moluska	*4. Linckia laevigata*	2	3	10	1	9
	5. Tridacna spp.	0	24	26	1	10
	6. Drupella spp.	0	6	7	2	25
	7. Phyllidia varicosa	0	15	39	10	3
	8. Chromodoris elisabethina	0	0	7	4	1
	9. Notodoris minor	0	0	0	4	2
Porifera	*10. Rhabdastrella globostellata*	12	27	16	12	6
	11. Theonela swinhoei	0	10	0	7	4
	12. Oceanatia acinensis	1	15	0	1	2
Coelentrata	*13. Fungia* spp.	97	115	148	72	24
Total		**179**	**817**	**820**	**288**	**146**

4. Diversity and abundance of coral fish

Reef fish diversity and abundance are essential components of coral reef ecosystems, contributing significantly to their ecological balance. These parameters exhibit dynamic fluctuations across different locations and time periods. Observations conducted over five months on various transplantation media using dead coral substrates are illustrated in Fig. (6), revealing substantial spatial and temporal variations.

Statistical analysis indicated significant differences in both species richness and fish abundance among the different transplant media. The highest species count and fish abundance were recorded on massive dead coral substrates, which performed comparably to natural coral. Notably, in July, both massive and branching dead coral substrates exhibited significantly higher fish abundance than natural coral. Other substrate types, such as rubble and tabulate dead coral, also yielded better results than the control areas, which were primarily dominated by loose rubble.

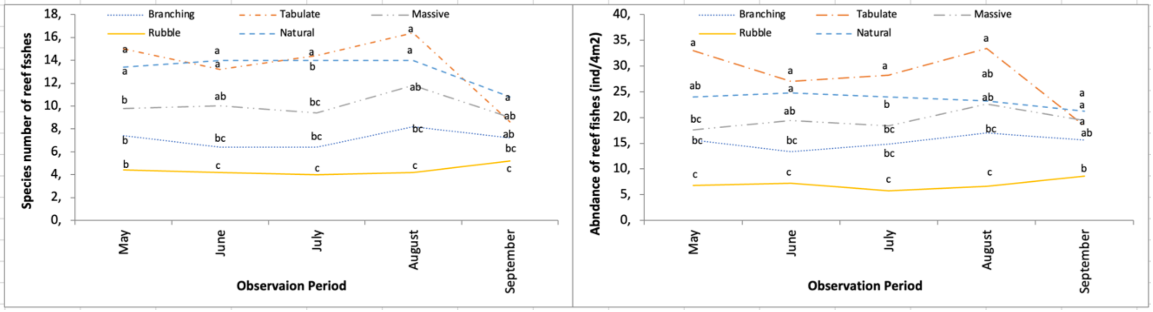

Fig. 6. The dynamics of species richness (a) and abundance of reef fish (b) on various dead coral substrates as attachment media in coral transplantation for 5 months of observation

The different letters above the graph in each month of observation show a significant difference in the 5% alpha based on the analysis of variance.

DISCUSSION

The high live coral cover observed in natural coral areas (control) can be attributed to stable environmental conditions and a well-balanced ecological structure among community members, particularly between producers and consumers. In contrast, live coral cover at the three transplantation sites—using dead coral substrates—was significantly higher than that of the control area, which was primarily composed of rubble. The observed increase in live coral cover at these transplantation sites over two years is a direct outcome of the coral transplantation efforts. A study by **Fujiwara and Omori (2004)** similarly reported that 21 months after coral transplantation in Sekisei Lagoon, Japan, live coral cover had increased in several locations. While coral fragmentation may initially reduce reproductive potential due to tissue injury, once healed, transplanted corals resume larval production, thereby contributing to reef regeneration **(Guest *et al.*, 2007)**.

The high abundance of *Didemnum molle* across all substrates—both dead and natural coral—is due to its common presence in tropical coral reefs. This tunicate species forms colonies and attaches firmly to substrates through its multiple zooids. Moreover, *D. molle* contains mycosporine-like amino acids (MAAs), which offer protection against UV radiation in shallow waters **(Hirose *et al.*, 2006)**.

Another widely distributed and abundant species was the solitary coral *Fungia* spp., found across all dead and natural coral substrates. *Fungia* is often considered an indicator of reef degradation and thrives on a variety of substrates, including reef slopes, reef flats, and sandy seabeds **(Hoeksema, 2012)**. It also possesses a unique ability to avoid harmful interactions with competing organisms **(Hoeksema & De Voogd, 2012)**.

Rhabdastrella globostellata was also abundant across all substrates. This sponge species, a common reef component, is recognizable by its rounded morphology and its adaptability to various surfaces, including branching dead coral and rubble. Its low predation rates are attributed to chemical defenses, as it produces bioactive compounds such as stellettins and rhabdastrellic acids **(Tasdemir *et al.*, 2002; Li *et al.*, 2010)**.

The bivalve mollusk *Tridacna* spp. was highly abundant across all dead and natural coral substrates. This widespread species is common in Indo-Pacific coral reefs and fulfills several ecological functions, including serving as a food source for predators and scavengers. Its shell supports epibiont colonization, while its mantle cavity hosts commensal and ectoparasitic organisms. Its presence in shallow waters is closely linked to the zooxanthellae in its tissues, which supply essential nutrients **(Neo *et al.*, 2015)**.

Phyllidia varicosa, a widely distributed sea slug, was also observed in high abundance. Found throughout the Indo-West Pacific, including the Red Sea, *P. varicosa* primarily feeds on specific prey such as anemones, gorgonians, and sponges inhabiting both dead and natural coral substrates. These sponges are often cryptic and encrusting, typically covered in sediment, and may only become visible once consumed by *P. varicosa* **(Yasman, 2003)**.

Reef fish diversity and abundance were notably higher on massive dead coral substrates compared to other transplantation media (tabulate, branching, and rubble), closely resembling values observed in natural coral reefs. This trend is likely due to the extensive growth of macroalgae—such as turf and fleshy algae—on massive coral surfaces, which attract herbivorous fish like the parrotfish. Grazing marks left by the parrotfish were evident on massive coral substrates, suggesting a high density of benthic organisms. **(Bonaldo *et al.*, 2011)** reported that parrotfish grazing leaves deep excavation scars on massive corals, which in turn promote the growth of filamentous algae and other benthic fauna.

Additionally, branched coral fragments transplanted onto massive dead coral substrates effectively attracted coral reef fish, particularly corallivorous species. These fish employ three primary feeding strategies: polyp feeding, mucus feeding, and skeleton feeding **(Cole *et al.*, 2008)**. For instance, the tulip wrasse (*Labrichthys unilineatus*) feeds on coral mucus, a rich energy source. Meanwhile, skeleton-feeding fish can significantly alter reef structures through their feeding activity **(Bellwood *et al.*, 2003)**. Branching corals also provide critical microhabitats for various reef fish species, especially those in the families Pomacentridae (damselfish) and Gobiidae (gobies), which are primarily planktivores or omnivores **(Coker *et al.*, 2013)**.

CONCLUSION

Coral transplantation using branching, massive, and tabulate dead coral substrates significantly enhanced live coral cover and increased reef fish species richness and abundance compared to the rubble substrate control areas. Notably, in July, massive dead coral substrates supported a greater number of fish species and individuals than the natural coral controls. Although no significant differences in live coral cover were observed among the three transplanted substrate types, all exhibited significantly higher cover than the rubble-dominated control areas.

Benthic communities also showed positive responses, with massive and tabulate substrates attracting more species and individuals compared to other treatments. Algal cover dynamics were primarily driven by fluctuations in filamentous algae, which varied significantly in June and July, while coralline algae cover remained relatively stable throughout the observation period

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