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# Coral recruitment enhancement in fish shelter media composed of fly ash and nickel slag on Obi Island, South Halmahera

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ABSTRACT

*The reefcube, a modular structure, serves as a primary habitat for fish and aids in the recruitment of new coral. The reefcube is predominantly made from fly ash and nickel slag, by-products of pyrometallurgy process that contain high content of CaO, MgO, dan $SiO_2$. These compounds aid in the calcification process of newly recruited corals. This project has been conducted since 2021, which includes deployment processes, monitoring, and data collection. The data collection methods involve randomly sampling natural coral recruits that have grown on the modular structures and measured periodicaly. So far, the coral growth ranged from 2.41 cm to 12.90 cm over the course of two years. The observed genera include Acropora, Isopora, Pocillopora, Millepora, Porites, and all of which have shown significant growth on the Reefcube. There were 24 fish families recorded during the monitoring period, with the Pomacentridae family accounting for 53% of all sightings. The most commonly observed size range was between 0-5 cm and 16-20 cm, which represented 29% and 28% of the total observations. Within this size range from Pomacentridae and Acanturidae family. Several individuals of the species Abudefduf vaigiensis from the Pomacentridae family were notably present.*

## Introduction

The coral reef ecosystem is a vital aquatic environment for biodiversity, serving as a feeding ground, nursery, and spawning ground for various marine organisms. Coral reefs are among the most species-rich habitats (Moberg & Folke, 1999). Indonesia has the second-longest coastline in the world, after Canada, resulting in extensive coastal and coral reef areas (Chamdareno *et al*., 2019). Coral reefs are characteristic of tropical waters and provide habitat for a diverse range of marine life, exhibiting high productivity and diversity. The marine biodiversity found in the Indonesian Archipelago, the Philippines, and the Solomon Islands is so rich that this region is referred to as the Coral Triangle. Within this area, a total of 605 coral species have been identified, accounting for 83% of all species found in the Indo-Pacific region and 76% of global species (Veron *et al*., 2010). Obi Island is one of the islands located within the Coral Triangle.

Fish are one of the marine organisms most affected by the conditions of coral reef ecosystems, particularly demersal fish. Demersal fish occupy the spaces between coral reefs as feeding, breeding, and nursery grounds. Current efforts to improve coral reef ecosystems include the installation of artificial reef structures, which serve as fish shelters and increase the available habitat for marine life, especially fish. The long-term goal of these artificial reefs is to function as fish shelters that enhance fish populations, thereby increasing future fish catches.

Reefcubes are engineered modular artificial reef structures designed to provide biogenic habitats for fish and serve as substrate for the settlement of coral larvae (planulae). Constructed from environmentally inert materials safe for nature, these cubes replicate the complex topography of natural coral reefs, facilitating larval attachment and subsequent recruitment. Over time, the successful colonization of these structures by coral larvae promotes the development of emergent ecosystems, enhancing biodiversity and attracting a variety of marine taxa. This ecological process not only contributes to the restoration of coral populations but also bolsters the resilience of marine ecosystems against anthropogenic stressors, including climate change

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and habitat degradation. Furthermore, the modular design of reefcubes allows for adaptability in deployment and maintenance, positioning them as a sustainable intervention in marine conservation practices.

The reefcube is predominantly made from fly ash and nickel slag, which are by-products of powerplant and pyrometallurgy nickel processing consecutively. In term of recycling and reuse, nickel slag repurposed for road construction, brick, and artificial reefs.

According to tests conducted by the accredited laboratory, the composition of Ca, Mg, and Si in the form of CaO, MgO, and $SiO_2$ in fly ash and nickel slag is as follows: fly ash contains approximately ±16% CaO, ±14% MgO, and ±26% $SiO_2$, while nickel slag contains around ±0.9% CaO, ±22% MgO, and ±61% $SiO_2$. The combination of calcium, magnesium, and silica in the substrate is crucial for supporting the growth of coral larvae and the overall health of coral reef ecosystems. A substrate rich in these three minerals will enhance the likelihood of coral larvae successfully attaching and thriving.

Coral recruitment is the process by which coral larvae attach to and begin to grow on new substrates, representing a crucial step in the coral life cycle. This process typically occurs after the reproduction phase, when coral larvae (planulae) are released from the parent colony and float until they eventually settle and colonize suitable areas. Coral recruitment is vital for the recovery and regeneration of coral reefs, as well as for contributing to the biodiversity of marine ecosystems (Hughes & Connell, 1999).

Another beneficial component found in fly ash and nickel slag for the coral recruitment process is iron (Fe), which is needed in small amounts for the photosynthesis of symbiotic algae (zooxanthellae) living within coral tissues (Ali *et al.*, 2011). The iron content in fly ash is approximately ±15%, while in nickel slag, it is around ±7%, primarily in the form of $Fe_2O_3$.

This study focuses on the application of by-products from nickel processing that possess significant potential to increase the probability of successful attachment of coral larvae. Additionally, we intend to examine the process of coral recruitment as the larvae mature and develop on the modular reefcube structures. Furthermore, we will monitor the presence of fish residing within these modular structures.

## Materials and Methods

### Location and time of research

The study starts in 2020 with the production of the modular reefcubes, followed by their deployment from 2021 to 2023, and continuing with monitoring and data collection. The materials used in the construction of the artificial reef with reefcubes include nickel slag, fly ash, and cement, in a ratio of 2:1:1. The cubes were then shaped to create hollow structures measuring 40 x 40 cm (Figure 1).

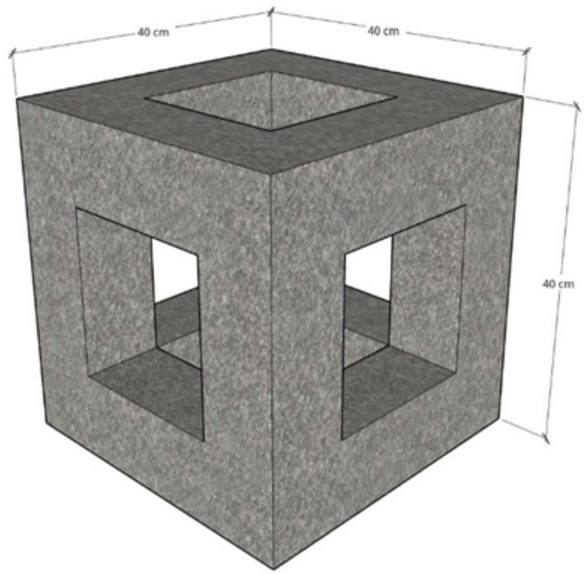



**Figure 1.** Shape of the Reefcube

The reefcubes were positioned and organized to create a structured installation in an area defined by rubble and sandy substrates, at an average depth of 5 meters (Figure 2). The chosen site for the deployment of the reefcubes possesses a wide and flat sandy substrate and is located adjacent to a natural coral habitat. This location aims to enhance the probability of coral larvae settling on the reef cubes during spawning periods. A total of 1,696 reef cubes have been installed on the seafloor at various places.


**Figure 2.** Research Location Map

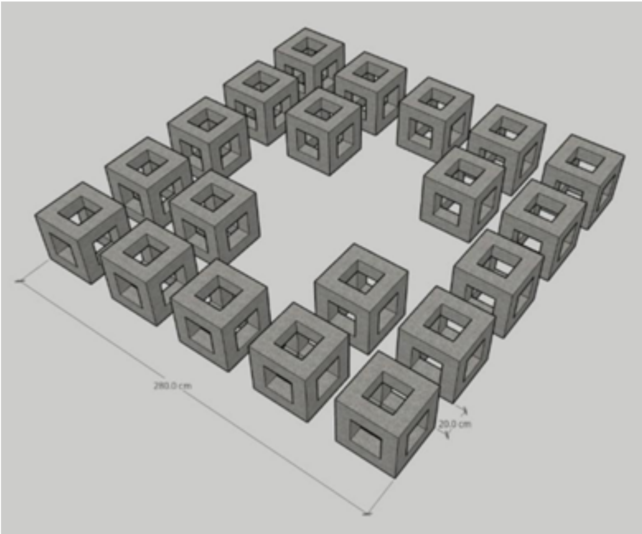



**Figure 3.** Example of the Modular Structure of Reefcubes

## Sampling dan data analysis

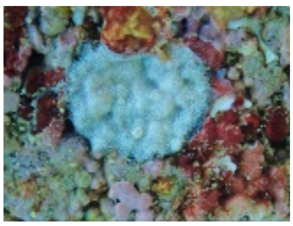
The continuous monitoring and data collection for the sampled reefcube structures began with their installation in March 2022 (Figure 3a) and continues to this day. This method necessitated the direct monitoring of the reefcube and the biota that began inhabiting the structures, followed by a descriptive analysis. This method directly observed and collected coral data through underwater photography, which was then analyzed on land using the CPCE (Coral Point Count with Excel extensions) software. The Reef Fish data were collected using the UVC (Underwater Visual Census) technique, which involved a 10-meter transect with a 2-meter width extending laterally on both sides (Hill & Wilkinson, 2004, with modifications). The acquired data were analyzed using Repeated Measures ANOVA in IBM SPSS.

## Results

Around three months after the placement and arrangement of the reefcubes on seabed, there are signs of life on the reefcube surface, and other biota started to use them as a habitat and foraging ground. The following table summarizes the visual observations of changes in the condition of the reefcubes (Table 1):

**Table 1.** Visual Observation Results of the Mechanisms of Reefcube Condition Changes Leading to Coral Recruitment

| Year | Month | Condition of Reefcube |
|---|---|---|
| 2022 | March | Placement process and restructuring of reefcubes (Figure 3a) |
| | May | Biofilm begins to appear (Figure 3b) |
| | June | Biofilm thickens, tunicates emerge (Figure 3c) |
| | August | Coralline algae appear (Figure 3d) |
| | September | Increased coralline algae density and size; coral recruitment <1 cm begins (Figure 3e) |
| | October | Further increase in coralline algae density and size; coral recruitment <1 cm continues |
| | November | Coralline algae grow larger and thicker; recruitment measurements begin (Figure 3f) |
| 2023 | February | Biofilm is covered by coralline algae; soft corals begin to grow (Figure 3g) |
| | April | Presence of giant clams *(Tridacna squamosa)* (Figure 3i) |
| | November | Octopus *(Octopus vulgaris)* begins to inhabit the reefcube structure (Figure 3k) |
| 2024 | June | Lola snails *(Trochus niloticus)* inhabiting the reef structure (Figure 3j) |
| | October | Moray eel *(Gymnothorax javanicus)* starts to inhabit the reefcube structure (Figure 3l) |

a 
b 
c 
d 

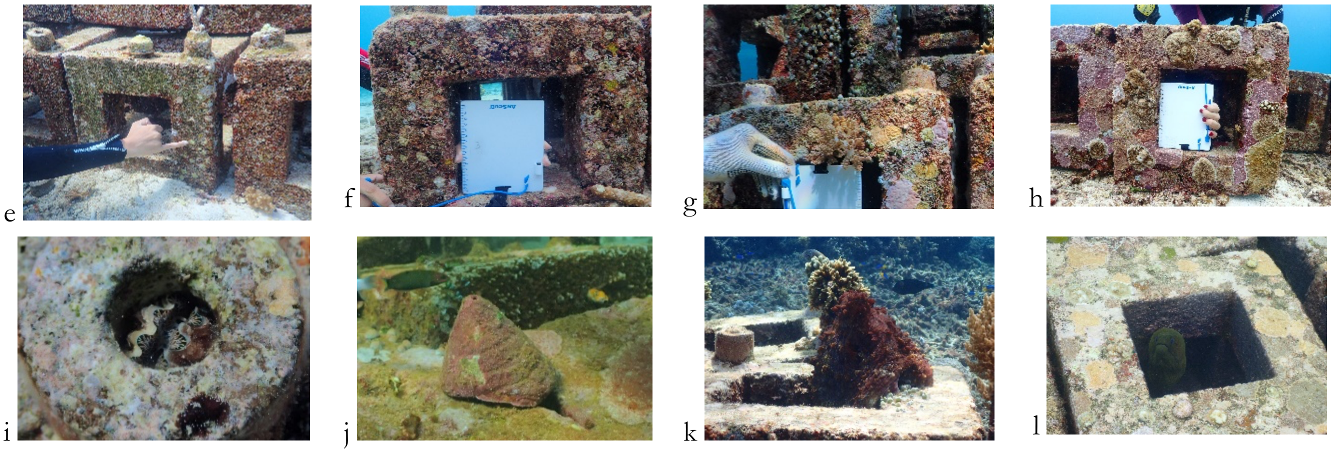



**Figure 3 (a, b, c, d, e, f, g, and h)** Visual Observation Results of The Mechanisms of Reefcube Condition Changes from Biofilm Development to Coral Recruitment; **(i, j, k, and l)** Marine Biota Occupying the Reefcube Besides Fish.

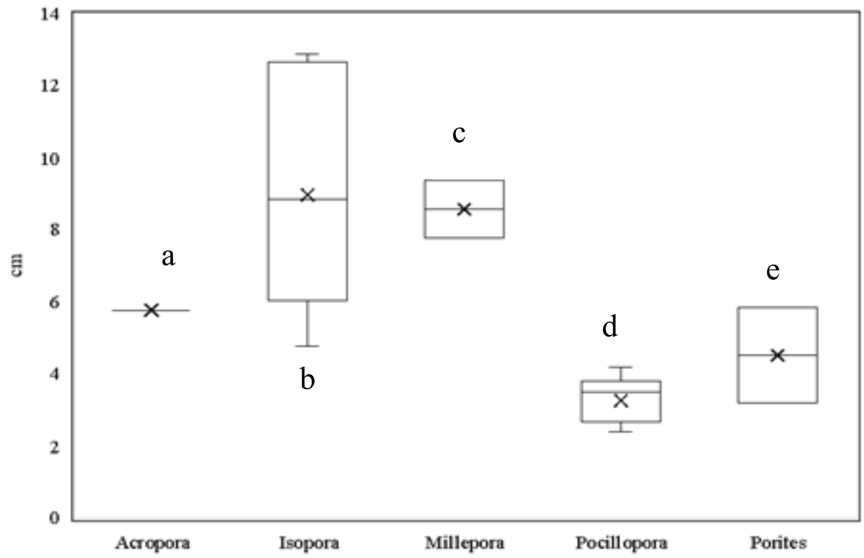



**Figure 4.** Coral Growth Rate Over Two Years

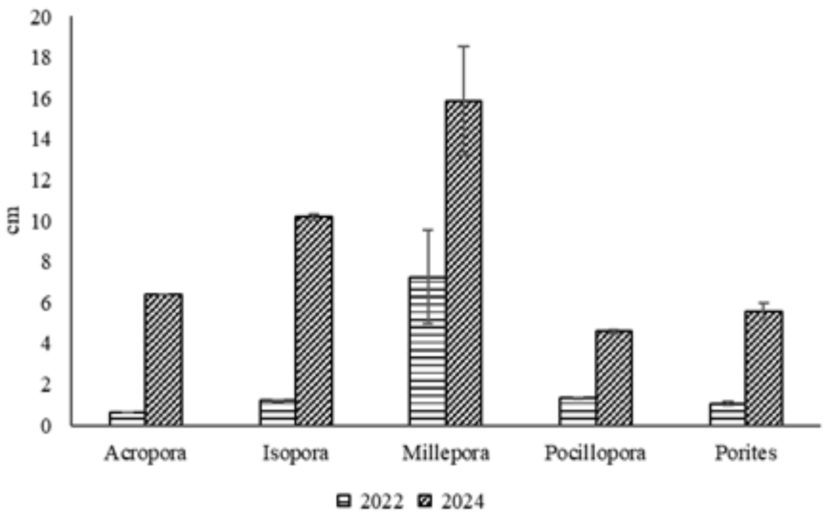



**Figure 5**. Average Growth By Genus for the Years 2022 and 2024

**Table 2.** ANOVA Results for Year and Genus Variables with Coral Recruitment Growth

| Variabel | Factor | df | F | P |
|---|---|---|---|---|
| Year | Growth | 1 | 93.131 | 0.000 |
| Genera | | 1 | 4.987 | 0.01 |
| Year*Genera | | 4 | 7.184 | 0.002 |

The measurements taken in 2022 and 2024 revealed significant results ($P<0.05$). Coral growth showed significant increases across all sampled genera, ranging from 2.41 cm to 12.90 cm after two years. The growth rate can vary between coral colonies, depending on species, colony age, and reef location. Corals are relatively slow-growing colonies, with growth rates typically around 0.1 to 10 cm in height per year (Clark, 1995).

## Discussion

### Coral recruitment procces

The formation of coral reef ecosystems is a protracted process that commences with the sexual and asexual reproduction of corals. Gametogenesis, a process of sexual reproduction, involves the release of male and female gametes from the same polyp or from different polyps within the same fertilized colony. After the release of the gametes, the parent polyp or the water column can undergo fertilization. As a result of this process, planula larvae emerge, swimming freely during the free-swimming phase, guided by currents and waves. Eventually, the planula settles on a rigid substrate and forms a new coral colony. As these colonies grow, they develop into larger structures (Richmond & Hunter, 1990). This project aims to facilitate this reproductive mechanism by providing modular reefcubes as a suitable substrate for coral planula settlement.

This process starts with the formation of biofilm on the modular reefcubes (Figures 3b & c). Biofilm is a thin layer composed of microbial colonies, including bacteria, algae, fungi, and other microorganisms, that adhere to specific surfaces of substrates (Bicknell, 1986). These microorganisms are bound to each other and to the substrate using a substance known as extracellular matrix, which is a mixture of polysaccharides, proteins, and DNA. The presence of minerals in the substrate, particularly calcium, iron, magnesium, and silica, enhances the growth and complexity of biofilm. CaO in the reefcube material reacts with $CO_2$ dissolved in seawater, facilitated by biofilm, to form more stable $CaCO_3$. This biofilm acts as a biochemical trigger that accelerates the carbonation process. Additionally, MgO can be transformed into $MgCO_3$ (dolomite) (Yus *et al.* 2024).

The biofilm serves as an initial habitat for the growth of coralline algae (Figure 3d). Coralline algae contribute to reef structure by depositing calcium carbonate. They create a more stable substrate suitable for coral planula attachment. The structure formed by coralline algae provides a safe environment for planula to settle and grow. Coralline algae support the ecosystem by supplying essential nutrients for planula development, thereby contributing to the successful colonization of corals (Goreau, 1963). The presence of coralline algae often indicates the health of the coral reef ecosystem. The biofilm and coralline algae play vital roles in transforming materials into a substrate rich in $CaCO_3$, MgO, and silica, but they do so in different ways. Biofilm acts primarily in the initial biochemical process to assist calcium carbonate precipitation, while coralline algae form a stable and biologically attractive natural substrate for coral larvae.

Once the planula is swimming freely in the ocean, it uses cilia to navigate and search for an ideal settlement location. Coralline algae are particularly attractive substrates for planula due to their calcium carbonate-rich surfaces and other chemical compounds that support coral growth. Coral planulae often choose to settle on substrates already coated with coralline algae, as these algae release bioactive compounds that stimulate the metamorphosis of the planula into a polyp. These compounds are regarded as chemical signals that inform the planula of the substrate's suitability for growth (Freire *et al.* 2019).

### Genera of coral recruitment

The genera *Acropora, Isopora, Pocillopora, Millepora*, and *Porites* have been observed growing on the reef cubes. The initial selection of coral recruits for monitoring was performed randomly on the reefcube structure, which will undergo frequent monitoring thereafter. Statistical analyses show that each genus has significant growth ($P<0.05$) (Figures 4 & 5). The genera *Isopora* and *Pocillopora* exhibited greater growth on the modular reefcubes in comparison to the other genera. This was affected by the natural coral reef environment surrounding the reefcubes, where a significant quantity of *Isopora* was discovered.

*Pocillopora*, as a pioneering genus in coral environments, was very widespread.

*Isopora and Pocillopora* are known for their high reproductive capabilities through both sexual (gamete release) and asexual (fragmentation) means. They produce numerous planulae (coral larvae) that have a higher chance of settling and developing on suitable substrates. These genera can adapt to various environmental conditions, including warmer water temperatures and salinity fluctuations. This flexibility allows them to be more resilient to environmental changes that can affect other coral recruitments. The corals from these genera have relatively rapid growth rates compared to some other coral species. This rapid growth enables them to quickly dominate newly settled areas and fill gaps in disturbed coral reef ecosystems (Villanueva *et al.* 2011; Masse *et al.* 2012).

In contrast to *Isopora* and *Pocillopora*, *Acropora, Porites,* and *Millepora* experienced less recruitment due to factors such as differing reproductive strategies, environmental sensitivity, specific substrate requirements, lower environmental stress resistance, and weaker adaptability to climate changes. Typically, *Acropora* and *Millepora* utilize broadcast spawning, releasing gametes (eggs and sperm) into the water simultaneously. This strategy heavily depends on ideal environmental conditions during spawning, and any disturbances (e.g., excessive heat or poor water conditions) can reduce fertilization success (Kaniewska *et al.* 2015). The *Porites* genus also utilizes broadcast spawning but has a different reproductive cycle and longer maturation time, which can decrease recruitment frequency (Brown *et al.* 2020). Conserverly, *Pocillopora* typically uses a brooding strategy, allowing larvae to grow within the parent polyp and release them when they're ready to settle, which provides them with an advantage in identifying suitable substrates and boosting recruitment opportunities (Ward, 1992). The *Isopora* genus exhibits a more flexible and effective reproductive strategy, adapting to various environmental conditions (Villanueva *et al.* 2011).

**Water quality**

The success of coral recruitment growth is influenced by the water quality parameters around the study site (Figure 6). Temperature values ranged from 28.15 to 30.13°C. The ideal temperature for coral larval growth generally lies between 24-29°C (Salm & Clark, 1989). While 30°C is at the upper limit, it still supports coral larval growth; however, prolonged exposure to temperatures above 30°C can cause stress to larvae and potentially lead to issues such as coral bleaching or larval mortality.

The optimal salinity for coral larvae is typically around 30-35 ppt. Salinity is a critical limiting factor for coral life, as corals struggle to survive in low salinity conditions (Goreau *et al.* 1979). The salinity values around the modular reefcubes are between 32.78 and 33.65 ppt. The parameter of dissolved oxygen (DO), pH, and light penetration were also within favorable ranges for coral recruitment growth. The water pH that supports coral growth should ideally range from 7.8 to 8.4, while optimal dissolved oxygen levels for coral larvae are generally above 5 mg/L, with light penetration (clarity) more than 5 meters (PP No.22, 2021).

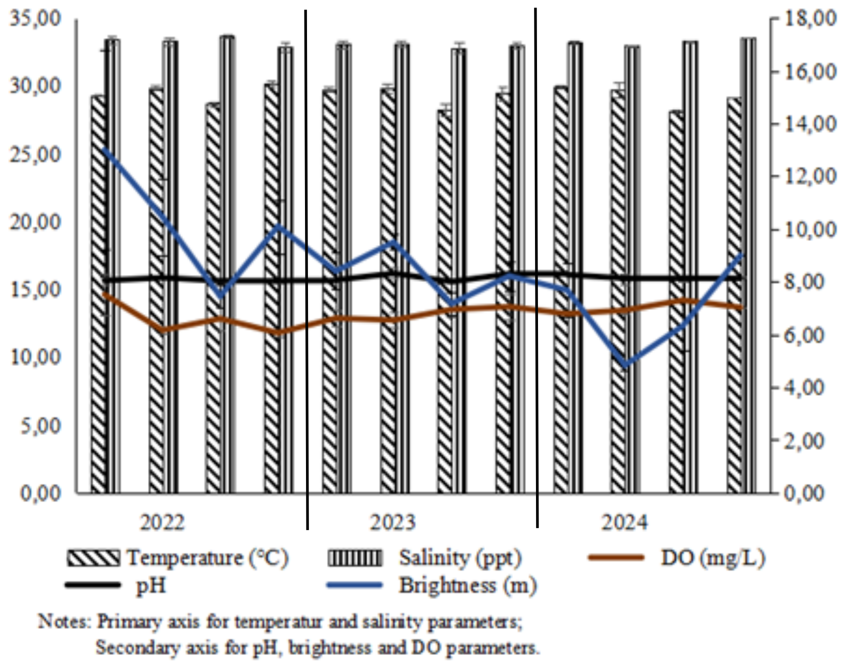



**Figure 6.** Water Quality Measurement in the Area of Reefcube Deployment.

As the population of microscopic biota inhabiting the modular structure increased, various exotic macrobiota began to utilize the reefcubes as their habitat. The exotic species observed on the reefcubes include octopus *(Octopus vulgaris*), giant clam *(Tridacna squamosa)*, lola snail *(Trochus niloticus),* and moray eel *(Gymnothorax javanicus)* (Figures 3i, j, k, and l).

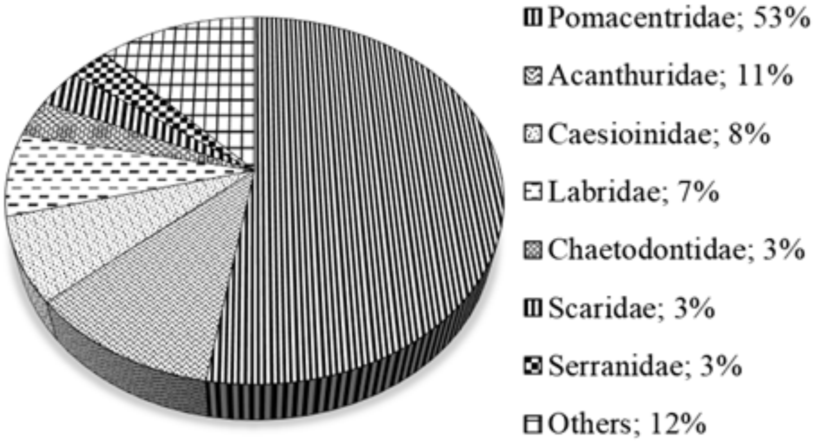



**Figure 7.** Composition of Families Occupying the Modular Reefcube Structure.

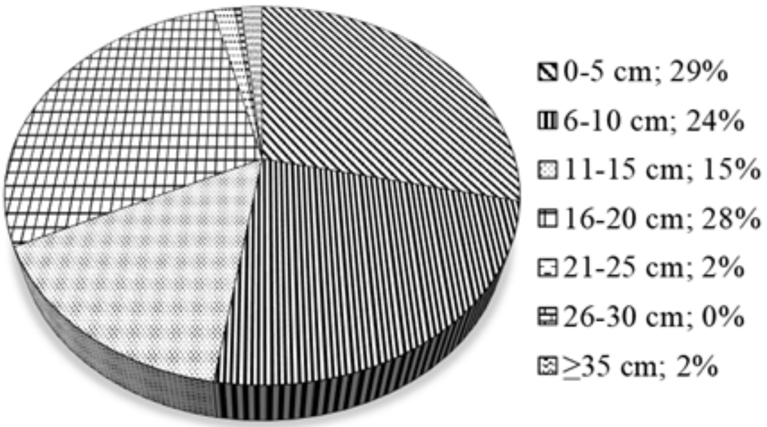



**Figure 8.** Size Composition of Fish Occupying the Modular Reefcube Structure.

**Reef fish observed in reefcube**

Over a two-year monitoring period, 24 families, 58 genera, and 128 species of reef fish have been documented inhabiting the modular reefcube structures. The majority of fish family compositions consist of 53% Pomacentridae and 11% Acanthuridae (Figure 7).

Species from the Pomacentridae family, such as *Pomacentrus coelestis*, *Dascyllus reticulatus*, and *Abudefduf vaigiensis*, frequently inhabit the modular reef cubes. Simultaneously, *Ctenochaetus striatus* and *Zebrasoma scopas*, both belonging to the Acanthuridae family, are often observed. The most common fish size seen was 0-5 cm, comprising around 29% of the total, followed by the 16-20 cm size at 28% (Figure 8). Those size ranges typically within the Pomacentridae and Acanthuridae families.

The Acanthuridae and Pomacentridae families dominate the early stages of artificial reef colonization due to their classification as omnivores, planktivores, and herbivores, allowing them to exploit the algae growing on the structures. Their adaptability to new environments, rapid reproductive cycles, and territorial behavior (particularly in Pomacentridae) further facilitate their success. Additionally, the initial lack of competition enables these species to reproduce in large numbers. Their role in controlling alga growth creates favorable conditions for other organisms, including corals, to thrive on the modular reefcubes (Hylkema *et al.*, 2020). The modular reefcube structures also housed the herbivorous Scaridae family, accounting for only 3% of the total recorded fish.

However, other economically important fish species from families such as Serranidae (groupers), Lethrinidae (emperors), and Lutjanidae (snappers) are populating the reefcubes in lesser quantities. Nevertheless, fish from the Caesionidae family were more dominant, comprising 8%. Edrus & Suharti (2017) categorize species of Caesionidae as planktivores, often feeding in the vicinity of the reefcubes where many planktonic microorganisms are present.

Based on data regarding the fishing ground around Obi Island, the location of the modular reefcube deployment also utilize by local villagers for fishing bottom-dwelling and small pelagic fish. Thus, there is hope that the establishment of these modular reef structures will lead to an increase in economically important fish thriving and developing in the area.

## Conclusion

Coral recruitment can substantially increase on modular structures composed of fly ash and nickel slag. The mineral composition of these materials promotes activities ranging from biofilm formation to the development of coralline algae and the growth of coral recruits. The genera *Isopora* and *Pocillopora* demonstrated the most successful development and were commonly observed on the modular reef cubes. Furthermore, reef fish from the families Pomacentridae and Acanthuridae were the most frequent inhabitants of the reef cubes.

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