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Early Fish Community Development in a 3D-Printed Artificial Clay Reef System in Pujada Bay, Philippines

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A B S T R A C T

This study assessed the early fish assemblage associated with a 3D-printed Artificial Clay Reef (ACR) deployed in Pujada Bay, City of Mati, Davao Oriental, six months after installation. Using a modified non-destructive Fish Visual Census, the study documented fish abundance, species composition, fishery category, trophic groups, and diversity indices. Results recorded 250 individuals from 27 species and 11 families. The assemblage was dominated by non-target reef-associated fishes, particularly pomacentrids, indicating that small-bodied fishes were among the earliest users of the structure. The presence of target species suggests initial functional roles related to herbivory, detritus removal, and trophic regulation. Overall, the ACR showed early habitat potential; however, continued monitoring is needed to confirm long-term rehabilitation success.

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INTRODUCTION

Coral reef ecosystems are among the most important coastal habitats because they provide shelter, feeding grounds (Bahinting et al., 2022; Montemayor, 1991; Toring-Farquerabao et al., 2021), nursery areas, settlement substrates, and structural refuge for reef-associated fishes (Ménard et al., 2012). However, many coral reef habitats continue to decline due to climate change, coastal development, sedimentation, destructive fishing practices, overfishing, and other human-induced pressures. As natural reef structures degrade, artificial reefs have increasingly been used as habitat enhancement and fisheries rehabilitation tools because they can provide additional hard substrate, increase habitat complexity, and support fish colonization, recruitment, and refuge (Bohnsack et al., 1994; Hylkema et al., 2020; Paxton et al., 2018).

In the Philippines, artificial reefs have a long history as part of coastal fisheries rehabilitation and marine resource management. Their use emerged partly in response to declining coastal fish production and the overexploitation of traditional fishing grounds (Montemayor, 1991; Munro & Balgos, 1995; *State of the Coral Triangle*, 2014). Early artificial reef initiatives in the country were implemented by academic institutions, government agencies, and coastal resource management programs, with artificial reefs intended to provide habitat, shelter, feeding areas, nursery grounds, settlement substrates, and sanctuary functions for fish and other marine organisms (Munro & Balgos, 1995). However, Philippine artificial reef experiences also emphasize that artificial reefs require careful planning, appropriate site selection, regular monitoring, and fisheries regulation because poorly managed structures may function mainly as fish-aggregating devices rather than as true habitat rehabilitation tools (Bahinting et al., 2022; Montemayor, 1991; Toring-Farquerabao et al., 2021). The WorldFish/ICLARM volume *Artificial Reefs in the Philippines* documents these concerns, including the use of materials such as tires, metals, concrete blocks, bamboo, and synthetic ropes, as well as the need to evaluate their management and ecological effects (Munro & Balgos, 1995).

Recent innovations in marine rehabilitation have introduced three-dimensional printing as a new approach in artificial reef design. Compared with conventional concrete, rock, bamboo, tire, or other hard-substrate artificial reefs, 3D-printed reef structures can be designed with controlled shapes, cavities, holes, surface textures, and microhabitat spaces that more closely mimic the structural complexity of natural reefs. Berman et al., (2023) reported that ceramic materials are applicable for artificial reef construction, and that parametric design and 3D printing can produce morphological diversity in reef structures. Yu et al. (2025) also investigated 3D-printed terracotta artificial reefs and reveals the potential of 3D-printed ceramic structures to improve both coral restoration outcomes and broader reef ecosystem recovery. Further studies suggest that 3D-printed ceramic or clay-based structures may provide bio-inspired shelter spaces, settlement surfaces, and microhabitats for reef-associated organisms (Berman et al., 2023, 2025; Kalam et al., 2018).

Although artificial reefs have long been used in the Philippines, most local initiatives and studies have primarily focused on conventional reef materials and broad fisheries enhancement goals. In contrast, the early development of fish assemblages on 3D-printed clay reef systems remains poorly documented in Philippine coastal waters. This gap is important because 3D-printed clay-based artificial reefs represent an emerging reef rehabilitation approach (Higgins et al., 2022), yet their effectiveness in supporting fish abundance, species richness, diversity, trophic structure, and habitat use is still insufficiently understood.

This study assessed the fish assemblage associated with the 3D-printed Artificial Clay Reef (ACR) deployed in Pujada Bay, City of Mati, Davao Oriental, approximately six months after installation. The ACR was installed within the Pujada Bay Protected Landscape and Seascape, in an area with nearby coral patches, seagrass, and mangrove ecosystems that may support fish recruitment, shelter, and ecological connectivity. Using a modified non-destructive Fish Visual Census, this study documented fish abundance, species composition, trophic groups, and diversity indices within the ACR. The findings provide an initial ecological snapshot of how reef fishes utilize a 3D-printed clay-based artificial reef and contribute baseline information for evaluating its potential as an emerging reef rehabilitation technology in the Philippine setting.

THEORETICAL REVIEW

This study is anchored on five complementary ecological theories: habitat complexity theory, artificial reef colonization theory, ecological succession theory, functional diversity theory, and reef resilience theory. Habitat complexity theory explains that structurally complex reef environments provide more shelter, refuge spaces, settlement surfaces, feeding areas, and microhabitats for reef-associated organisms. In coral reef systems, structural complexity strongly influences fish abundance, species richness, habitat use, and community organization because complex habitats provide protection from predators and support different ecological niches (Ménard et al., 2012; Rooker et al., 1997). This theory is directly relevant to the 3D-printed ACR, as its modular clay design, cavities, holes, and elevated surfaces are intended to mimic the physical complexity of natural reefs and provide habitat for small reef fishes, recruits, and other associated organisms.

Artificial reef colonization theory supports the idea that newly deployed artificial reefs may be rapidly occupied by reef-associated fishes, especially when the structures provide hard substrate, shelter, and feeding opportunities. Previous studies have shown that artificial reefs can be colonized within the first few months after deployment, with fish abundance, richness, and assemblage structure changing during the early post-installation phase (Bohnsack et al., 1994; Hylkema et al., 2020; Paxton et al., 2022). In the present study, the occurrence of 250 individuals from 27 species six months after installation suggests early fish colonization and habitat use within the ACR. However, this should be interpreted cautiously as an initial ecological response rather than definitive evidence of long-term restoration success.

Ecological succession theory further explains that artificial reefs undergo gradual biological development through time. During the early stage, newly installed reef structures are often used by small-bodied, mobile, and generalist species, while larger target species and higher trophic-level predators may become more established only as habitat complexity, prey availability, benthic cover, and ecological interactions increase. The dominance of non-target reef-associated fishes and the low abundance of piscivores in the ACR may therefore reflect an early successional stage of fish community development. This is consistent with studies indicating that artificial reef fish communities are dynamic and may shift in species composition, abundance, richness, dominance, and trophic structure as the reef matures (Becker et al., 2017; Hicks et al., 2025; Vivier et al., 2021).

Functional diversity theory emphasizes the ecological roles of species rather than species richness alone. In reef ecosystems, different trophic groups contribute to important ecological functions, including plankton feeding, algal grazing, detritus removal, benthic invertebrate predation, and trophic regulation. The presence of planktivores, omnivores, herbivores, benthic invertivores, herbivore-detritivores, and piscivores within the ACR suggests the early development of a functionally varied assemblage. Herbivorous and herbivore-detritivorous fishes, such as siganids, scarids, and acanthurids, are particularly important because they help regulate algal growth and maintain benthic habitat condition, which are essential processes in reef ecosystem functioning (Cheal et al., 2013; Edwards et al., 2014).

Finally, reef resilience theory provides the broader conservation basis of the study. Reef resilience refers to the capacity of reef ecosystems to resist disturbance, recover after stress, and maintain ecological functions over time. Functional groups such as herbivorous fishes contribute to reef resilience by reducing algal dominance and supporting conditions favorable for coral and benthic recovery (Cheal et al., 2013; Edwards et al., 2014). In the context of the ACR, the presence of functionally important fishes may indicate an early contribution to reef ecological processes; however, resilience cannot be confirmed from one-shot sampling alone. Therefore, the findings should be framed as evidence of early colonization, habitat use, and initial functional representation. Long-term monitoring is necessary to determine whether the ACR can sustain fish diversity, improve evenness, increase trophic complexity, and contribute to reef rehabilitation outcomes over time (Becker et al., 2017; Vivier et al., 2021).

METHODOLOGY

Study Area

The ACR was deployed in Pujada Bay, specifically along the Guangguang Peninsula on the eastern side of the bay in the City of Mati, Davao Oriental, located along the Pacific coast of Mindanao. The assessment was conducted in July 2024, approximately six months after the installation of the ACR. The selected site is characterized by a relatively flat seabed with nearby coral patches, a substrate depth of at least 60 cm within the 20 m^2 deployment area, a maximum seawater depth of seven meters, and an approximate distance of 150 meters from the shoreline. Adjacent mangrove and seagrass ecosystems were also observed, indicating ecological connectivity among coastal habitats that may support fish recruitment, shelter, and foraging activities. The site is situated within the Pujada

Vol. 5, No. 7, 2026: 2613 - 2626

Bay Protected Landscape and Seascape (PBPLS), which benefits from existing management and protection mechanisms, making it suitable for reef rehabilitation efforts.

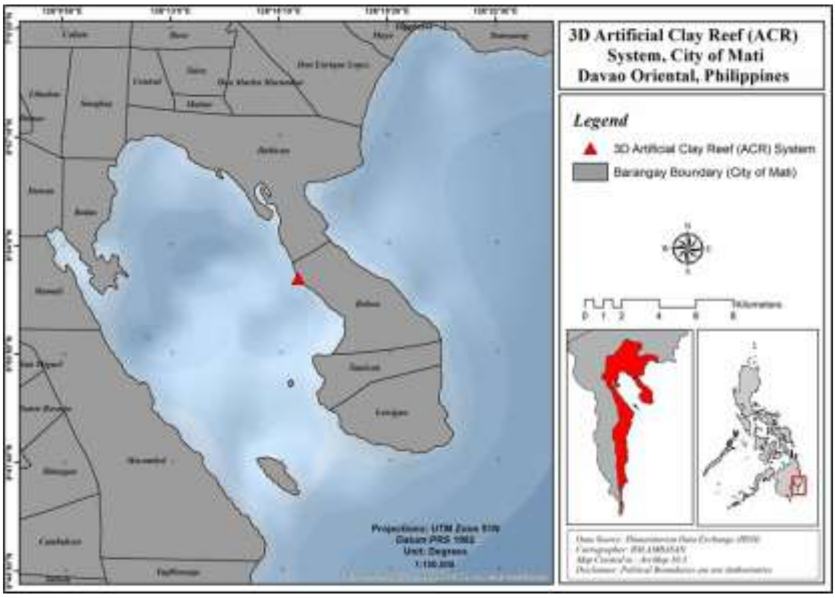

Figure 1. Location of the 3D Artificial Clay Reef (ACR) System in Pujada Bay, City of Mati, Davao Oriental, Philippines.

Sampling design

A modified non-destructive Fish Visual Census (FVC) was conducted within the ACR to monitor fish abundance and assemblage structure. The assessment focused primarily on the structure rather than the surrounding habitat. A 10 m transect was laid parallel to the shoreline and adapted to the actual size and configuration of the ACR. The FVC consisted of three complementary methods: point count for mobile species, belt transect for conspicuous demersal species, and line transect for cryptic and juvenile fishes.

Data Analysis

Fish visual census data were first encoded in a spreadsheet and organized by family, scientific name, fishery category, trophic group, and number of individuals recorded within the ACR. Each species was treated as a separate taxonomic unit, while the number of individuals observed per species was used as the basic abundance value for analysis. The total number of individuals was computed by summing all species-level counts, while species richness was determined as the total number of fish species recorded during the census.

Descriptive statistics were used to summarize the early fish assemblage associated with the ACR. Relative abundance was calculated for each species, family, fishery category, and trophic group using the formula:

$$\text{Relative abundance (\%)} = \left(\frac{\text{number of individuals in a given group}}{\text{total number of individuals recorded}}\right) \times 100$$

Fish categories were summarized as target and non-target species to describe the proportion of fishes with potential fishery importance . Trophic groups were classified based on known feeding ecology and were summarized to describe the functional composition of the assemblage. These included planktivores, omnivores, herbivores, benthic invertivores, herbivore-detritivores, and piscivores (*FishBase*, 2026).

Species diversity was analyzed using PAST software version 4.06b (Hammer et al., 2001). The Shannon–Wiener diversity index (H′) was computed to assess diversity by considering both species richness and the distribution of individuals among species (Ortiz-Burgos, 2016). Dominance was calculated to determine whether the assemblage was numerically controlled by one or a few highly abundant species. Evenness was also computed to assess how equally individuals were distributed across the recorded species. Higher H′ and evenness values indicate a more diverse and balanced assemblage, while higher dominance values indicate greater numerical dominance by a limited number of species.

Because the study was based on one sampling period and focused only on fishes observed within the ACR structure, the analysis was limited to descriptive community assessment. No statistical comparison with natural reef sites, control sites, or temporal monitoring periods were conducted. Therefore, the results were interpreted as an initial ecological snapshot of fish colonization and habitat use approximately six months after ACR installation, rather than as conclusive evidence of long-term reef rehabilitation success.

RESULTS

Fish visual census data from the ACR were organized according to family, species, fishery category, trophic group, and number of individuals. Frequency counts and percentages were used to summarize abundance, species richness, family composition, category composition, and trophic structure. Diversity was further assessed using the Shannon–Wiener index, dominance index, and evenness.

Table 1. Fish species composition, fishery category, trophic group, and individual abundance recorded in the Artificial Clay Reef.

Family	Scientific Name	Category	Trophic Group	Individual Count
Pomacentridae	*Abudefduf sexfasciatus*	Non-target	Planktivore	8
Pomacentridae	*Acanthochromis polyacanthus*	Non-Target	Planktivore	1
Acanthuridae	*Acanthurus leucocheilus*	Target	Herbivore/detritivore	18
Acanthuridae	*Acanthurus thompsoni*	Target	Planktivore	2
Pomacentridae	*Amblyglyphidodon curacao*	Non-Target	Planktivore	60
Tetraodontidae	*Canthigaster sp.*	Non-Target	Omnivore	3
Epinephelidae	*Cephalopholis argus*	Target	Piscivore	2
Labridae	*Cheilinus chlorourus*	Target	Benthic Invertivore	2

Labridae	*Choerodon anchorago*	Target	Benthic Invertivore	2
Syngnathidae	*Corythoichthys sp.*	Non-target	Benthic Invertivore	2
Pomacentridae	*Dischistodus melanotus*	Non-Target	Herbivore	3
Labridae	*Halichoeres chloropterus*	Non-Target	Benthic Invertivore	3
Labridae	*Halichoeres scapularis*	Non-Target	Benthic Invertivore	15
Blenniidae	*Meiacanthus grammistes*	Non-Target	Planktivore	1
Pinguipedidae	*Parapercis clathrata*	Non-Target	Benthic Invertivore	3
Pinguipedidae	*Parupeneus indicus*	Target	Benthic Invertivore	2
Mullidae	*Parupeneus multifasciatus*	Target	Benthic Invertivore	5
Pomacentridae	*Pomacentrus alexanderae*	Non-Target	Omnivore	62
Pomacentridae	*Pomacentrus burroughi*	Non-Target	Herbivore	4
Pomacentridae	*Pomacentrus grammorhynchus*	Non-Target	Herbivore	8
Labridae	*Scarus ghobban*	Target	Herbivore	13
Labridae	*Scarus globiceps*	Target	Herbivore	2
Nemipteridae	*Scolopsis bilineata*	Target	Piscivore	1
Siganidae	*Siganus fuscescens*	Target	Herbivore	22
Siganidae	*Siganus guttatus*	Target	Herbivore	3
Labridae	*Stethojulis bandanensis*	Non-Target	Benthic Invertivore	1
Labridae	*Thalassoma hardwicke*	Non-Target	Benthic Invertivore	2

The FVC recorded 250 individuals, representing 27 species from 11 families. Non-target species dominated the assemblage with 176 individuals or 70.4%, while target species accounted for 74 individuals or 29.6%. The most abundant family was Pomacentridae, mainly represented by *Pomacentrus alexanderae* with 62 individuals and *Amblyglyphidodon curacao* with 60 individuals. Other common species were *Siganus fuscescens* with 22 individuals, *Acanthurus leucocheilus* with 18 individuals, and *Halichoeres scapularis* with 15 individuals.

In terms of trophic groups, planktivores were the most abundant with 72 individuals, followed by omnivores with 65, herbivores with 55, benthic invertivores with 37, herbivore-detritivores with 18, and piscivores with 3 individuals. The Shannon–Wiener diversity index of 2.494 indicates moderate diversity, while the dominance value of 0.1389 suggests that no single species completely dominated the assemblage. However, the evenness value of 0.4483 shows that individuals were unevenly distributed among species.

DISCUSSION

The fish assemblage documented in the ACR indicates that the structure began serving as a habitat for reef-associated fishes approximately six months after installation. A total of 250 individuals, encompassing 27 species and 11 families, were recorded, demonstrating early colonization and habitat utilization within the ACR. This observation is consistent with previous artificial reef studies, which have shown that newly deployed structures are rapidly occupied by reef-associated fishes when they provide hard substrate, shelter, refuge, and feeding opportunities. Bohnsack et al. (1994), Hylkema et al. (2020) and Paxton et al. (2018) similarly reported that artificial reefs can support the development of fish assemblages during the early post-deployment period, although community structure may continue to change as the reef matures.

The predominance of non-target species, particularly pomacentrids, suggests that small-bodied reef-associated fishes were among the earliest and most successful colonizers of the ACR. This pattern is ecologically plausible, as small reef fishes typically depend on structurally complex habitats for shelter, predator avoidance, feeding, and daily refuge. Previous studies have highlighted the importance of habitat complexity in shaping reef fish abundance, species richness, and assemblage structure. Ménard et al. (2012) and Rooker et al. (1997) observed that reef fishes frequently utilize holes, crevices, and shelter spaces, which are key features of both natural and artificial reef habitats. In the present study, the high abundance of *Pomacentrus alexanderae* and *Amblyglyphidodon curacao* indicates that the cavities and structural spaces of the 3D-printed clay modules provided suitable microhabitats for small reef fishes. Comparable tropical artificial reef studies have also documented rapid colonization by reef-associated fishes, with Pomacentridae and Labridae often among the dominant families in early assemblages (Suyatna et al., 2019). Similarly, García-Baciero et al. (2026) found that the damselfish *Pomacentrus chrysurus* dominated fish assemblages across rehabilitation structures in Tioman Island, further supporting the observation that pomacentrids are frequently among the earliest and most abundant users of newly available reef habitats.

The observed assemblage provides further evidence that artificial reef communities undergo ecological succession. Early-stage artificial reefs are typically dominated by mobile, small-bodied, and generalist species, whereas larger target fishes and higher trophic-level predators tend to become more prevalent only after habitat structure, benthic colonization, prey availability, and ecological interactions are more fully established. The low abundance of piscivores in the ACR is consistent with an early successional stage rather than a mature reef fish community. This notion is supported by Paxton et al. (2018), who reported that fish colonization on newly deployed artificial reefs follows a temporal trajectory, with initial dominance by schooling and planktivorous fishes preceding the development of more demersal assemblages. Similarly, demonstrated that artificial reef design and structural complexity influence fish abundance, biomass, assemblage composition, and functional group attraction (Hylkema et al., 2020, 2023). Long-term and synthesis studies indicate that artificial reef assemblages are dynamic, changing in abundance, richness, trophic composition, and dominance over time (Becker et al., 2017; Hicks et al., 2025; Higgins et al., 2022; Vivier et al., 2021). Recent research also supports a cautious interpretation of early colonization: El Rahimi et al. (2026) reported lower species richness and Shannon diversity on artificial reefs compared to nearby natural reefs six months after deployment, while Carver et al. (2025) found limited fish community development and low residency one year after installation. Therefore, the present ACR assemblage should be regarded as an early developmental stage that has begun to support reef-associated fishes, but ongoing monitoring is necessary to determine whether larger target fishes, piscivores, higher diversity, and more stable trophic structure will emerge as the reef matures.

Within the Philippine context, these findings contribute to ongoing discussions regarding the role and limitations of artificial reefs in coastal resource management. Previous local studies and reviews have demonstrated that artificial reefs can provide habitat and fish aggregation benefits, but their effectiveness depends on appropriate design, site selection, protection, monitoring, and fisheries regulation. Montemayor (1991), Munro & Balgos (1995), Toring-Farquerabao et al. (2021), and Bahinting et al. (2022) emphasized that artificial reefs should not be considered stand-alone solutions to reef degradation. Instead, they should be integrated with broader habitat protection, fisheries management, and long-term ecological monitoring. The present study supports this cautious perspective. Although the ACR exhibited early habitat potential, the available data are insufficient to conclude that it has achieved reef rehabilitation or fisheries enhancement outcomes.

In summary, the results indicate that the 3D-printed ACR in Pujada Bay provided early habitat for reef-associated fishes and supported an assemblage with multiple trophic roles. However, as the study was based on a single sampling period and lacked comparison with natural reef or control sites, the findings should be regarded as baseline evidence of early colonization and habitat use. Continued monitoring is necessary to determine whether species richness, evenness, trophic complexity, target fish abundance, benthic colonization, and assemblage stability increase as the ACR matures. Future assessments should include repeated fish visual census surveys, incorporation of natural reef and non-reef control sites, benthic cover assessment, water quality monitoring, and evaluation of fishing or disturbance pressure at the deployment site.

CONCLUSIONS AND RECOMMENDATIONS

The 3D-printed Artificial Clay Reef in Pujada Bay showed early potential as a habitat for reef-associated fishes approximately six months after installation. The fish assemblage recorded within the structure consisted of 250 individuals representing 27 species and 11 families, indicating early colonization and habitat use. The assemblage was dominated by small-bodied non-target fishes, particularly pomacentrids, suggesting that the structural spaces, cavities, and shelter features of the ACR may have provided suitable microhabitats for early reef fish users. Although non-target species were more abundant, the occurrence of target species such as rabbitfishes, surgeonfishes, parrotfishes, and groupers indicates that the ACR was also beginning to support fishes with important ecological roles related to herbivory, detritus removal, benthic foraging, and trophic regulation.

The trophic composition of the assemblage, which included planktivores, omnivores, herbivores, benthic invertivores, herbivore-detritivores, and piscivores, suggests early functional differentiation within the developing fish community. However, the moderate Shannon–Wiener diversity value, low evenness, and limited abundance of piscivores indicate that the assemblage remained uneven and was still in an early stage of ecological development. Therefore, the findings should be interpreted as baseline evidence of early fish colonization and habitat use, rather than conclusive proof of long-term reef rehabilitation or fisheries enhancement success.

It is recommended that regular long-term monitoring be conducted to determine whether fish abundance, species richness, evenness, trophic complexity, target fish occurrence, and community stability improve as the ACR matures. Future monitoring should use standardized and repeated Fish Visual Census surveys across different seasons to account for temporal changes in recruitment, habitat use, and fish movement. Comparative assessments with nearby natural reef sites and non-reef control areas should also be included to determine whether the ACR is merely aggregating fishes or contributing to broader habitat enhancement and reef recovery.

FURTHER STUDY

This study is limited by its single sampling period, which provides only an initial snapshot of the fish assemblage associated with the 3D-printed ACR. Since reef fish communities may change over time due to seasonality, recruitment patterns, habitat development, fish movement, and environmental conditions, the findings cannot yet fully represent the long-term ecological performance of the ACR. The study also focused mainly on fish assemblage data; therefore, future research should include repeated monitoring, comparison with nearby natural reef and non-reef control sites, water quality assessment, benthic cover analysis, and coral or substrate colonization surveys. Future studies should also document fishing activity, anchoring, sedimentation, and other disturbance pressures around the deployment site, as these factors may influence fish colonization, habitat use, and community development.

To allow natural colonization and ecological succession to continue, the ACR site should be protected from fishing, anchoring, and other forms of physical disturbance. As an emerging reef rehabilitation approach, 3D-printed clay reef systems should be evaluated within broader coastal resource management strategies that include habitat protection, fisheries regulation, and long-term ecological monitoring. These additional studies will help determine whether the ACR is primarily aggregating fishes or genuinely contributing to reef recovery, habitat enhancement, and marine biodiversity conservation. This framing is consistent with the article's current limitation that the findings are based on one sampling period and should be treated as baseline evidence rather than conclusive proof of rehabilitation success.

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