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Strategic Deployment of Artificial Reefs for Enhanced Fisheries Management in Sediment-Rich Waters of Indonesia: A Case Study from Damas Beach

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ABSTRACT

Artificial reefs have been widely used to enhance marine biodiversity and support sustainable fisheries management. This study evaluates the ecological performance of artificial reefs in Damas Beach, Indonesia, assessing their impact on fish populations and environmental conditions from 2020 to 2024. Water quality was measured in situ, and a stationary visual census was used to analyze changes in species composition and habitat conditions. Results indicate increased turbidity and shifts in fish community structure including declines, stability, and the emergence of previously unrecorded type. These changes highlight the influence of water quality and habitat modifications on fish assemblages. The study also underscores the importance of integrating technology into fisheries management, such as real-time monitoring, sediment control strategies, and adaptive reef maintenance. Community involvement also plays a key role in ensuring long-term sustainability. Future efforts should focus on optimizing reef design to enhance structural complexity, reduce sedimentation, and strengthen ecosystem resilience. A strategic approach combining artificial reefs, advanced monitoring technologies, and stakeholder participation offers a viable solution for improving fisheries productivity while maintaining ecological stability in sediment-rich coastal environments.

1. INTRODUCTION

Artificial reefs have been found to replicate natural habitats, promoting the recovery of coral populations and supporting marine lives [1] emphasize that using materials like shipwrecks or concrete for artificial reefs significantly increases habitat availability for corals and reef fish, making them a crucial tool for conservation in degraded reef areas. Similarly, Ghiasian et al. [2] highlight the success of hybrid artificial reefs in reducing wave energy, which helps protect shorelines and provides more stable conditions for coral growth. These reefs can be constructed from various materials, including concrete, steel, and other environmentally friendly substances, each influencing the ecological dynamics of the surrounding marine habitat. Concrete is one of the most commonly used materials for artificial reefs due to its availability, low cost, and durability. Healthy coral reefs, characterized by high coral cover and structural complexity, are vital for maintaining diverse fish communities. For instance, studies have shown that the abundance of certain fish families, such as the Chaetodontidae, serves as indicators of coral reef health [3].

The installation of artificial reefs has been shown to attract diverse fish species, acting as aggregators that enhance local fish populations. Yuan et al. [4] highlight that artificial reefs offer habitats with higher structural complexity than open waters, which boosts species richness and diversity. That artificial reefs also found help to increase fish abundance in estuaries with limited habitats, providing crucial environments for fish populations [5]. Well-designed artificial reefs can quickly draw significant numbers of reef fish, revitalizing local food chains [6]. Additionally, artificial reefs often display more structural complexity than natural reefs, offering refuge from predators and improving fish survival, particularly near the edges of their geographic ranges [7]. Meanwhile the socio-economic benefits of artificial reefs are significant, as they not only improve fish stocks but also promote recreational activities like diving and fishing, leading to greater economic gains for local communities [8]. For example, artificial reefs have been shown to help alleviate fishing pressure on natural reefs, contributing to their conservation [9]. This dual function of enhancing fisheries productivity while preserving marine biodiversity highlights the crucial role artificial reefs play in modern marine management strategies.

Successful cases of implementing artificial reefs in Indonesia can be found in various regions, such as the Seribu Islands, Bali, and Lombok. According to Puspasari et al. [10], the installation of artificial reefs in the waters around Bali had a positive influence on fish communities. Notably, both the abundance and diversity of fish increased in areas surrounding the artificial reefs. The research observed a rise in the number of fish species and biomass following the installation, with some locations demonstrating a continual growth in fish populations over time. The structural complexity of the artificial reefs was identified as a critical factor in supporting fish populations, as these reefs provide essential habitats for shelter and feeding for a variety of fish species. In addition, the location of artificial reefs also affects the types and abundance of fish. Suspended artificial reefs, or those installed or hung above the seabed, tend to be inhabited by many planktivorous fish, as opposed to herbivorous demersal fish, such as croppers. On the other hand, artificial reefs placed on the seabed are more likely to be inhabited by a variety of predatory fish (piscivores), carnivores, and demersal herbivores [11].

The importance of this study lies in the effort to monitor the condition of the artificial reef at Damas Beach which has been installed for seven years. In September 2017, a total sinking of 25 cube artificial reefs was carried out in the coastal waters of Damas, which is expected to become a new ecosystem for coral, invertebrates and reef fish. This effort was carried out based on observations of coral cover in 2017 of 39.52% [12] dominated by massive growth and its cover was classified as poor because much debris was found due to fishing nets caught in this area. Observations in 2020 by Luthfi et al. [13] recorded 16 families of coral reef fish, with an abundance of 1.73 individuals per square meter, and Apogonidae being the most dominant family at 0.41 individuals per square meter around Damas artificial reefs. After 4 years, in 2024 a second observation will be carried out, to see the presence of fish around the artificial coral reef, both in type and number, as a parameter for the success of implementing artificial reefs in Damas Beach. This monitoring is crucial to evaluate the extent to which the artificial reef has succeeded in functioning as a habitat for reef fish and other marine organisms. By monitoring the condition of the artificial reef periodically, we can evaluate its effectiveness in supporting local biodiversity and identify the steps for improvement needed so that this artificial reef can continue to play a role in the recovery of the marine ecosystem. The results of this study are expected to provide important insights for the management and maintenance of artificial reefs in the future.

2. METHODOLOGY

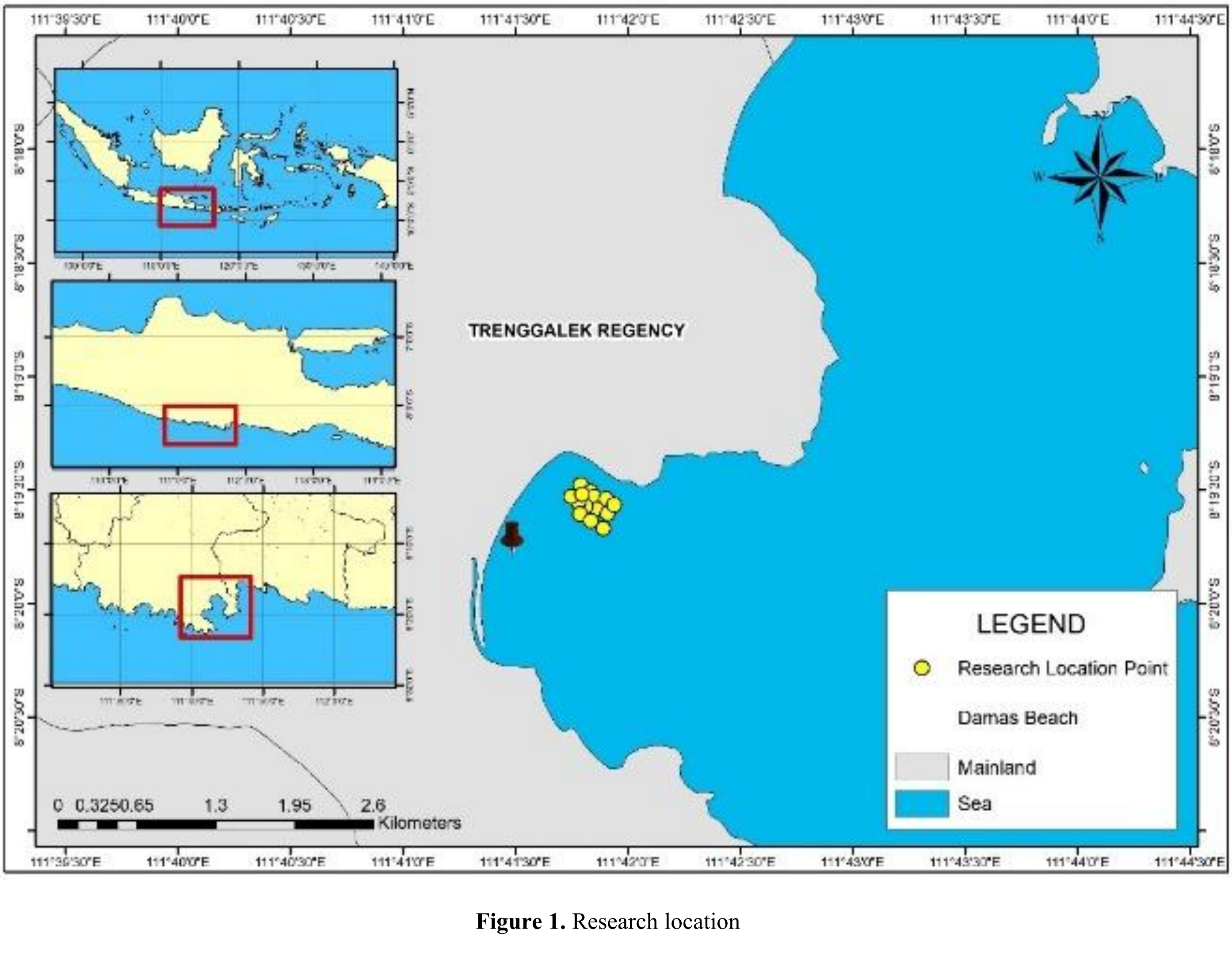

Figure 1. Research location

Damas Beach was selected as the research site due to its coral reef ecosystem's vulnerability to threats posed by the use of environmentally unfriendly fishing gear. According to data from 2013-2019 [14] coral cover in this area has declined. To address this issue, rehabilitation efforts have been undertaken through the deployment of artificial reefs since 2017. This initiative provides a unique opportunity to study the long-term ecological dynamics of a disturbed coral reef system. Additionally, the waters in this area exhibit high Total Suspended Solids (TSS) levels, indicating significant sedimentation that could disrupt coral reef sustainability [15]. While alternative locations along the southern coast of Java were considered, Damas Beach was prioritized due to the availability of baseline data, relatively good accessibility, and its importance to the local fisheries sector.

This research was conducted in the waters of Damas Beach, Karanggandu Village, Watulimo District, Trenggalek Regency. Artificial reefs (ARs) made of concrete were placed in 2017 with a total of 25 units submerged. Data collection for TB evaluation was carried out three years after its placement, namely in March 2020, and continued in the next study, namely August 2024 as a comparison. March 2020 falling within the first transition season, while August 2024 represents eastern season [16]. However, seasonal variations were not specifically considered during data collection. Sampling was conducted without regard to seasonal differences, which may introduce potential variability in the results. The research location map is shown in Figure 1.

2.1 Water quality monitoring

Water parameter data collection was carried out around the artificial reef placement point. The parameters were used temperature, salinity, brightness, sedimentation, and sea current (secondary data). Water parameter measurements were carried out in situ (field data collection) three times at each station. The tools used in measuring water parameters include AAQ Rinko for measuring temperature and salinity, Secchi disk for measuring water brightness, and sediment trap for collecting sedimentation rate data. Meanwhile, current speed data was obtained from the website https://podaac.jpl.nasa.gov/, which will then be processed and analyzed to obtain an average from each collection.

2.2 Reef fish monitoring

Reef fish surveys were performed using the stationary visual census method, covering both the entire surface of the artificial reefs (ARs) and a 5-meter radius surrounding each AR, delineated by imaginary lines (as shown in Figure 2). The 5-meter radius used for fish surveys was selected based on standard visual census protocols adapted for small-scale artificial reef monitoring in tropical waters. This radius allows for comprehensive assessment of fish assemblages associated with individual artificial reef units while minimizing edge effects from adjacent habitats or structures. Previous studies on artificial reef monitoring used similar radii to ensure coverage of fish utilizing the reef for shelter, feeding, or as a transit corridor, while excluding fish that may only be loosely associated with the structure [17].

This method allowed for a comprehensive and uniform assessment of fish abundance and species diversity in the vicinity of the ARs, providing valuable insights into the fish communities associated with these structures. Divers conducted the observations and captured the data using an Olympus TG underwater camera. Fish populations were monitored through direct underwater observation, focusing on individual modules of the artificial reef. Photographs and videos were taken to aid in species identification, which was primarily based on external morphological features seen during the dives. Any fish that could not be identified on site were photographed for later identification using various fish identification guides, and the number of individuals was recorded alongside their respective genera.

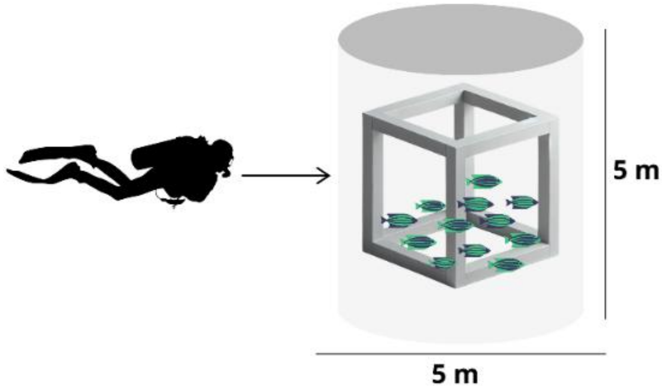

Figure 2. Monitoring method

The stationary visual survey method has several limitations, including observer bias that can affect species identification and abundance estimates, particularly for cryptic or fast-moving species. This method only covers species within the diver's field of view, potentially missing those occupying deeper crevices. Variations in fish behavior due to time of day, tidal phase, or diver presence also influence the results. More mobile species or those less dependent on artificial reefs tend to be underrepresented, limiting the method's ability to capture the full range of species utilizing the reef structure. Observations were conducted repeatedly (replicate observations) in each artificial reef module to improve data accuracy. Variability between observers was minimized through pre-survey training and cross-checking of species identification results and post-survey abundance recordings.

The abundance of reef fish is the number of fish found at an observation station per unit area of observation. The calculation of the abundance of reef fish can be calculated using the following formula:

$$K = \frac{\sum i}{A}$$

K = Total abundance of reef fish (ind/m²)
i = Number of fish (ind)
A = Area of observation transect (m²)

3. RESULTS AND DISCUSSION

3.1 Water quality parameter in artificial reefs

The following table presents the water quality parameters around the artificial reef (AR) area for the years 2020 and 2024, which are essential for assessing the environmental conditions and potential impacts on fish conditions.

Table 1. Water quality around AR

Parameters	2020	2024
Water clarity (m)	2.8-3.9	1.3-4.5
Water temperature (°C)	25.60-25.96	24.69-25.77
Turbidity (NTU)	0.3-4.32	19.00-35.78
Current Speed (m/s)	0.1-0.4	0-0.1
Salinity (ppm)	34.67-34.68	34.00-34.52
pH	8.26-8.41	7.3-8
DO (mg/L)	6.65-6.68	6.68-6.80

Note: Data 2020 Source [13, 18]

Water clarity measurements were carried out in-situ using a secchi disk showed values ranging from 1.3 to 4.5 m, thus showing quite notable variations. This variation in brightness is likely due to data collection being carried out during the east season which is usually marked by increased currents and strong winds [19]. The speed of the current in an area will affect the brightness of the area, where slow currents generated by coastal seiches can resuspend sediment from the seabed, leading to increased turbidity [20] leading to decrease water clarity in the water column. The availability of light is important for photosynthetic organisms and is influenced by factors such as water clarity and particulate matter. This influences the distribution of marine life and primary production, as organisms depend on light for energy [21].

The temperature at Damas Beach ranges from 24.69°C - 25.77°C, indicating a stable temperature that is good enough to support marine life, including around artifical reef area. With this relatively cool temperature, the coral ecosystem and other marine biota that require a certain temperature to adapt and survive are very helpful. Both coral and fish populations are susceptible to rising sea temperatures, which can impact their behavior, reproductive rates, and overall biodiversity. Changes in temperature may lead to alterations in fish physiology [22] and community structure, while in corals, thermal stress can trigger bleaching, ultimately resulting in coral mortality [23]. The sea surface temperature in the east season is relatively lower than in the west season, which ranges from 24.9°C - 30.7°C. The low temperature during the eastern season along the southern coast of Java, Bali, and Nusa Tenggara is caused by the eastern monsoon winds pushing surface water westward, triggering upwelling that brings cold water from the deeper layers to the surface [24].

The salinity values recorded at Damas Beach ranged from 34.00 ppt to 34.52 ppt, which is the normal range (33-34 ppt) for marine waters. Stable salinity is important for maintaining the osmotic balance of marine organisms, especially around AR. Fluctuations in water salinity can induce stress in fish, disrupting homeostasis and normal physiological functions [25]. During the east season, currents from the Indian Ocean can bring water with slightly higher or lower salinity depending on the water conditions around the south coast, but it will not significantly affect the existence of marine biota as long as it is still within the normal range.

The pH levels observed ranged from 7.3 to 8, with slightly lower than 2020. The pH is still within the acceptable range for marine biota, although variations can affect the calcification process in corals. Dissolved oxygen (DO) levels ranged from 6.68 to 6.80 mg/L, these values are optimal for marine biota (> 5 mg/L). Higher DO levels indicate that the waters are healthy and capable of supporting marine ecosystems. High oxygen levels can be influenced by optimal photosynthesis processes, as nutrients present in the water are easily carried to the upper layers, allowing them to be utilized in photosynthesis and produce oxygen [26].

Meanwhile, turbidity levels in the study exceeded the recommended threshold of < 5 NTU for marine ecosystems, with values recorded as high as 35.78 NTU in 2024. This indicates a high sediment load in the water column, which can reduce light penetration, affect photosynthesis, and potentially inhibit coral growth in the artificial reef area. Reduced light penetration impacts photosynthetic organisms such as algae and seagrasses, thereby affecting the entire food web structure. In addition, sedimentation deposits can smother corals and even prevent their natural growth and reduce the effectiveness of AR structures as habitats for marine biota.

Overall, based on the data in Table 1 regarding water quality around the artificial reef (AR) in 2020 and 2024, the most noticeable fluctuation is observed in the turbidity parameter. In 2020, turbidity values ranged from 0.3-4.32 NTU, whereas in 2024, increased to 19.00 to 35.78 NTU. This sharp increase in turbidity is likely linked to a rise in sedimentation within the waters surrounding the AR. Previous research at Damas Beach, shows TSS levels during the rainy season reached 145 mg/L, far exceeding the 20 mg/L threshold [15].

The increase in sedimentation can be attributed to various factors, including land erosion carried by river flows, human activities in coastal areas such agricultural runoff, and changes in land use in upstream regions [27, 28]. Sediment particles entering the waters can reduce water clarity, which also shows a decline from 2020 to 2024, as presented in the table. Moreover, elevated turbidity levels can have profound ecological consequences, especially when they exceed the tolerance limits of marine biota.

The results of measurements of the current speed in the waters of Damas Beach in August were 0.1 m/s. The current speed at the research location is relatively weak, because it is still below 0.5 m/s which is an indicator of moderate currents [29]. A surface currents also influence the vertical movement of ocean water, which is crucial for nutrient cycling and oxygen distribution that important for marine species [21]. Low current speeds increase the potential for sedimentation around the AR [30] which in the long term can cover artificial reefs and inhibit the growth of biota especially for coral recruit settlement and survival [31]. Sedimentation from solid mud particles carried during the surface run off process due to erosion can cover the surface of coral reefs [32]. Ultimately, this combination of high turbidity levels and weak currents creates an unfavorable environment for the growth and sustainability of artificial reefs, threatening their ecological function as a refuge for marine biodiversity.

3.2 Fish dynamics on artificial reefs in 2020 and 2024

According to Figure 3, a comparison of fish populations in 2020 and 2024 on the Damas artificial reef, there are changes in the composition of fish families in both years. In 2020, there were several families recorded but did not appear again in 2024, namely Acanthuridae, Apogonidae, Blenniidae, Fistulariidae, Nemipteridae, Ostraciidae, Pinguipeidae, Solenostomidae, Tetrarogidae, and Tripterygiidae.

The presence of these families in 2020 indicates that the more artificial reefs at that time (22 units) supported higher species diversity. Changes in the structure and number of artificial reefs, which decreased to only 16 units, appear to affect habitat conditions that are favorable for certain families to persist or even emerge as new species. This difference indicates that the decrease in the number of artificial reefs not only impacts the abundance of fish populations, but also the composition of species presents at the site.

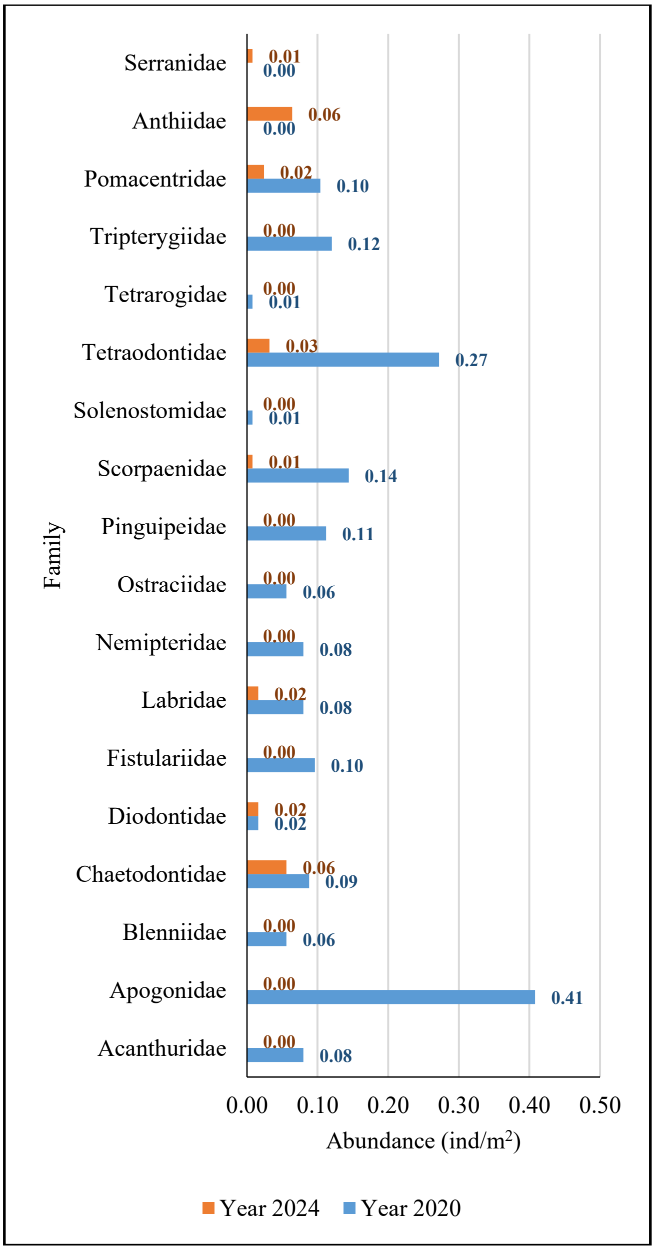

Figure 3. Reef fish abundances in Damas AR
Source: 2020 data from Luthfi et al. [13]

The observed differences in 2024 are likely also due to the artificial reef structure not being overgrown with macrofouling, corals, or another sessile biota. This can reduce the function of the reef as a shelter and food source for fish, so that its effectiveness in supporting marine ecosystem life becomes less than optimal. The biota attached to the artificial reef structure at Damas Beach includes ten types of macrofouling organisms, namely tubeworm, barnacle, hermit crab, bryozoa, green algae, tunicate, hydroid, brown algae, sponge, and red algae. Among these organisms, barnacle is the most dominant, covering about 66% of the total attached biota [33].

In 2020, a total of 16 fish families were recorded, with the highest abundance observed in Apogonidae (0.41) and Tetraodontidae (0.27). However, both families experienced a notable decline in population during the 2024 survey. Apogonidae, commonly known as cardinalfish, are typically found in shallow tropical waters, often inhabiting coral reefs, caves, and crevices. They are primarily nocturnal species [34]. Tetraodontidae (pufferfish), also prefer coral reef habitats but are adaptable and can be found on sandy bottoms, estuaries, muddy substrates, seagrass beds, and deep waters, with coral reefs serving as their primary environment [35].

Additionally, the Acanthuridae family, an important functional group of herbivorous fish that helps control competition between corals and algae [36] also experienced a decline in 2024, along with the reduction in Apogonidae and Tetraodontidae populations. This decline appears to be linked to the unsuccessful implementation of artificial reefs in the surveyed area, where the structures failed to develop sufficient coral growth, resulting in an environment that lacked the habitat complexity and resources necessary for many reef-associated fish species. Since coral reefs play a vital role in providing shelter, feeding grounds, and breeding sites, the inability of the artificial reefs to support coral colonization and growth likely led to unsuitable conditions for these fish, forcing them to either migrate to better-developed natural reefs or remain as transient visitors rather than establishing stable populations.

Meanwhile, the abundance of Chaetodontidae and Diodontidae remained relatively stable across both years. Chaetodontidae (butterflyfish) are typically found in coral reef and rocky habitats in tropical and warm waters, generally at depths of less than 20 meters, though some species inhabit depths exceeding 100 meters [37]. Meanwhile, Diodontidae (porcupinefish) are primarily benthic dwellers, often found near coral and rocky reefs, though certain species are also frequently observed in seagrass beds and sandy or muddy substrates at depths of up to 150 meters. One species has even been recorded in pelagic waters [38].

During the 2024 survey, two fish groups that were not recorded in 2020 were observed: the Serranidae family and the Anthiadinae subfamily. Serranidae, which includes groupers, are predominantly demersal fish commonly found in coral reef and rocky habitats with varied substrate relief [39]. During the survey, groupers from the Epinephelus genus were observed resting on the substrate, positioned alongside artificial reefs. Meanwhile, Anthiadinae, a subfamily within Serranidae, were observed schooling in large groups. These fish are small, brightly colored, and feed on zooplankton, either above coral reefs or near rocky substrates [40, 41].

Overall, this graph shows a shift in the composition of the fish community from 2020 to 2024, with some previously dominant families experiencing drastic declines and others maintaining or even increasing in numbers of individuals. These findings highlight the critical need for continuous monitoring and adaptive management of artificial reefs. To improve the effectiveness of ARs as sustainable fish habitats, future management efforts should focus on enhancing the structural complexity of ARs, addressing sedimentation issues, and ensuring long-term maintenance.

3.3 Artificial reef condition and fish assemblages

Hollow cube-shaped artificial reef structures generate variable airflow, with higher speeds in some areas and slower in others. While these cube structures are effective as fish shelters, more streamlined reef designs result in more efficient flow patterns and nutrient distribution for the marine organisms living within them [42]. Fish species diversity and abundance are also influenced by the complexity of artificial reef designs. For instance, the artificial reef on Nyamuk Island successfully increased fish abundance and diversity due to its complex design, which enhances surface roughness and provides protective spaces for fish. These structures, made from a mixture of cement and sand with holes for live coral transplantation, support coral growth and create a sustainable ecosystem [6]. Complex artificial reef designs not only offer better protection and breeding environments for fish species but also help reduce habitat competition and maximize food sources through the inclusion of buffer zones. These buffer zones, by maintaining adequate distances between reefs, support additional habitats in surrounding sand areas, enabling fish foraging and reproduction without disturbances. Moreover, buffer zones prevent overfishing by dispersing fish populations, making artificial reefs more effective in increasing biodiversity and maintaining ecosystem balance [43, 44].

Zhang et al. [45] found that a balance between closed and open areas in artificial reef structures increases shelter availability for reef fish, emphasizing the importance of internal complexity and rough surfaces in reef designs to maximize habitat utilization. Artificial reefs effectively enhance fish habitat, supporting densities, biomass, diversity, and species richness comparable to natural reefs. However, their effectiveness depends on geographic location and the materials used, requiring careful consideration of local environmental conditions during placement [7]. To achieve successful marine ecosystem conservation and fisheries management, particularly in developing countries, artificial reefs (ARs) must be designed and managed with attention to social, economic, and biological factors. Proper management can prevent negative impacts, such as decreased catches from overexploitation, especially in areas with limited monitoring. Therefore, long-term monitoring and community-based management are essential to ensure ARs function as sustainable conservation tools [46]. From a design perspective, setting complexity targets (CTPs) is critical to supporting biodiversity. By utilizing 3D CAD modeling, the geometric and informational complexity of ARs can be optimized to resemble natural habitats, supporting diverse and productive biotic communities. This approach offers a quantitative framework to improve the effectiveness of ARs in fostering healthy marine ecosystems [47].

There are several important aspects in the design and management of artificial reefs (AR) to be effective in marine ecosystem conservation and fisheries management, especially in developing countries. In the social, economic and biological contexts, AR requires careful management to avoid negative impacts such as decreased catches due to overexploitation, especially in areas with limited monitoring, therefore long-term monitoring and community-based management are needed for AR to be a sustainable conservation tool [46]. Setting complexity targets (CTPs) is essential for enhancing biodiversity in artificial reefs (ARs). By using 3D CAD models to adjust the structure's geometric complexity to resemble natural habitats, ARs can more effectively support diverse and productive marine ecosystems [47]. Factors contributing to the lacking performance of artificial reefs include inadequate design, environmental disruption, insufficient scale, unsuitable sites that impede species colonization, and a deficiency in long-term monitoring [48].

The artificial reefs at Damas Beach (Figure 4) have been deployed without a strategic plan, resulting in scattered placements that may adversely affect the local marine ecosystem. Some structures are positioned too close to natural coral reefs, potentially leading to ecological disturbances. For instance, studies suggest that maintaining a minimum buffer zone between artificial and natural reefs is crucial to prevent habitat overlap and resource competition [44]. In addition, some structures have been buried in sediments.

Figure 4. Documentation of artificial reef placements at Damas Beach showing two contrasting conditions — (A) Artificial reef structures placed too close to natural coral reefs, potentially causing ecological interference; (B) Artificial reef structures placed in barren sandy areas far from existing coral reefs, reducing their effectiveness as alternative habitats and buried in sediment

Source: Documentation, 2024

Conversely, other artificial reefs at Damas Beach are situated in barren sandy areas devoid of natural reef ecosystems. Such placements may be less effective, as they do not consider the habitat preferences of target marine species. The success of artificial reefs depends significantly on their location relative to existing habitats and environmental conditions [49].

Additionally, the current artificial reef structures at Damas Beach lack the necessary complexity to attract and support diverse marine life. Enhancing structural complexity is vital, as it provides shelter and breeding grounds for various species, thereby increasing biodiversity. Recent studies have emphasized the importance of incorporating intricate designs in artificial reefs to mimic natural habitats effectively [47].

In conclusion, the dynamics of fish communities observed on artificial reefs provide important insights for coastal biodiversity management. Changes in fish community composition, such as the loss of certain fish families (e.g., Apogonidae and Acanthuridae) or the increase in abundance of other families (e.g., Anthiidae), reflect environmental stress or habitat changes. These findings can be used to evaluate the effectiveness of artificial reefs in supporting ecosystem functions.

3.4 Implications for fishery management

The findings highlight the importance of ARs in supporting local fisheries by providing habitats for commercially valuable fish species. However, to optimize their benefits, ARs must be integrated into comprehensive fishery management plans.

1. **Regular Monitoring and Maintenance**: Regular

monitoring and maintenance of ARs are essential to ensure their effectiveness in providing suitable habitats for fish. Regular assessments allow stakeholders to identify any damage or degradation to the reef structures, such as sediment accumulation or biofouling, which may affect their function [50]. By implementing maintenance activities like cleaning sediment and enhancing the structural complexity, ARs can continue to provide adequate shelter and breeding grounds for marine life. Monitoring should include water quality assessments [51], and fish population surveys [52], to evaluate the ongoing effectiveness of ARs in supporting biodiversity.

2. **Community-Based Management**: The success of artificial reef (AR) projects depends on active participation from local communities, making human resource development essential. According to Isdianto et al. [53], engaging local fishers and community groups fosters ownership and responsibility, ensuring the long-term sustainability of Ars with considering the following things:

- **Community-Based Fishery Management Groups**: These groups oversee AR activities, including fish population monitoring [54] enforcing fishing regulations, and conducting maintenance.
- **Training Programs**: Essential for building community capacity [55], focusing on technical training: Knowledge of AR construction, deployment, maintenance, and handling issues like sedimentation and biofouling.
- **Environmental Awareness**: Artificial reefs (ARs) play a significant ecological role in marine biodiversity conservation by providing essential habitats for various marine species, enhancing fish populations, and contributing to the overall health of marine ecosystems. Understanding the multifaceted impacts of ARs on marine biodiversity is crucial for effective fisheries management and conservation strategies [56].
- **Monitoring Techniques**: The structural complexity of ARs provides refuge from predators and enhances feeding opportunities, which can lead to increased fish biomass in the vicinity of these structures. Skills in fish population surveys and water quality assessments [4].

3. **Sedimentation Control**: Sedimentation control is critical to maintaining the functionality and ecological value of artificial reefs. High sedimentation rates can bury reef structures, reducing their effectiveness as fish habitats and hindering coral growth [5]. Several approaches can be used to manage sedimentation:

- **Installation of Buffer Zones**: Establishing buffer zones around artificial reefs can help reduce the direct impact of sediment from coastal erosion. Vegetative barriers and sediment control structures can be used to minimize runoff from surrounding areas [57].
- **Sediment Traps**: Deploying sediment traps near artificial reefs is a valuable strategy for capturing sediment particles before they settle on reef surfaces [58]. These traps should be regularly cleaned to maintain their effectiveness. The insights gained from sediment trap studies can inform conservation efforts and enhance our understanding of sediment dynamics in coral reef ecosystems.
- **Erosion Control Measures**: Addressing coastal erosion through shoreline stabilization projects can help reduce the amount of sediment entering marine ecosystems. Techniques such as planting mangroves or installing seawalls can be effective in mitigating erosion [59]. These measures not only protect coastal infrastructure but also enhance ecological resilience, thereby contributing to the sustainability of coastal environments.
- **Water Current Management**: Understanding local water currents and strategically placing artificial reefs in areas with optimal flow can help reduce sediment buildup. By positioning artificial reefs in areas with optimal flow, it is possible to reduce sediment buildup and prevent stagnant water conditions that contribute to sediment accumulation [60].
- **Land Use Management in Upstream Areas**: Land use management in upstream areas plays a critical role in mitigating sediment runoff, particularly through the implementation of reforestation programs, promotion of sustainable agriculture, and enforcement of regulations against illegal logging. These strategies can significantly enhance watershed management, leading to reduced sediment loads in downstream water bodies [61].

4. **Coral Transplantation on Artificial Reefs**: This method has been proven effective in accelerating the recovery of damaged marine ecosystems, especially in areas with high sedimentation. A study in Kenya [1] demonstrated that transplanting coral fragments onto artificial structures can increase coral cover by up to 41% within two years, while also attracting economically valuable reef fish such as Lutjanidae and Acanthuridae. The selection of sediment-resistant coral species, such as Porites massive, as well as easily fragmented corals like Acropora, and the use of diverse coral fragments are crucial for enhancing colonization success and biodiversity [62]. This method has the potential to increase habitat complexity and support ecosystem recovery.

5. **Zoning and Regulation**: Implementing zoning and regulatory measures around artificial reefs (ARs) is crucial to prevent overfishing and ensure the sustainability of fish stocks. Designating AR areas as fishery reserves can reduce fishing pressure and allow fish populations to replenish [8]. In Indonesia, seasonal fishing bans during spawning periods are regulated under Regulation of the Minister of Marine Affairs and Fisheries No. 26/PERMEN-KP/2020, which prohibits the capture of especially yellowfin tuna (Thunnus albacares) in spawning areas from October to December to protect juvenile fish and improve recruitment rates.

Additionally, size limits on fish catches are encouraged to ensure that younger fish have the opportunity to mature and reproduce, as stipulated in Regulation of the Minister of Marine Affairs and Fisheries No. 59/PERMEN-KP/2020, which governs fishing routes and permissible fishing tools to support sustainable practices. Furthermore, restrictions on destructive fishing methods, such as trawling and the use of certain nets, are emphasized in Regulation of the Minister of Marine Affairs and Fisheries No. 28 of 2023, which mandates the implementation of measured fishing practices to safeguard marine ecosystems, including ARs.

6. **Design Improvements**: The effectiveness of ARs can be significantly enhanced through design improvements that increase their structural complexity and ecological functionality [63]. Incorporating features that provide more surface area and varied textures can promote coral growth and attract diverse marine species. Using eco-friendly materials that support marine life can further enhance the ecological value of ARs [64]. Site-specific considerations, such as current patterns and sedimentation rates, should be taken into account when designing and deploying ARs to ensure their long-term success.

7. **Long-Term Monitoring and Adaptive Management**:

Long-term monitoring frameworks are essential to track changes in fish populations and AR performance over time. Data collected through these frameworks can provide insights into the effectiveness of ARs and inform adaptive management strategies. For instance, if a decline in fish populations is detected, management plans can be adjusted to address potential causes, such as habitat degradation or increased fishing pressure [65]. Incorporating stakeholder feedback into the management process ensures that ARs continue to meet both ecological and socio-economic objectives [66]. Adaptive management allows for continuous improvement and ensures the sustainability of AR initiatives in the long run.

4. CONCLUSIONS

The implementation of artificial reefs at Damas Beach has proven to be a valuable strategy for enhancing fish biodiversity and providing robust support for sustainable fisheries management. The study conducted from 2020 to 2024 underscores the dynamic nature of fish communities associated with artificial reefs and emphasizes the critical role of technological advancements and strategic management in maximizing these structures' ecological and economic benefits.

Effective fisheries management utilizing artificial reefs requires not only careful design and strategic placement but also the integration of advanced monitoring technologies. These technologies can provide real-time data crucial for adaptive management, allowing for the optimization of reef performance in response to environmental changes and community dynamics. The application of such technologies in regular assessments can lead to more informed decisions regarding the maintenance and scaling of artificial reef projects.

Moreover, the study highlights the importance of community involvement in the sustainable management of artificial reefs. By leveraging local knowledge and fostering community stewardship, fisheries managers can enhance the effectiveness and acceptance of artificial reefs as tools for economic development and ecological preservation.

Looking forward, it is imperative that future initiatives integrate artificial reefs into comprehensive fisheries management plans. This should include considerations for technological enhancements that improve habitat complexity and ecological functionality, ultimately leading to healthier fish populations and more resilient marine ecosystems.

Local governments and fisheries managers need to integrate artificial reef monitoring into integrated coastal management programs. The establishment of community-based monitoring groups can encourage active participation of fishermen in monitoring changes in fish populations and reef conditions. In addition, government agencies are advised to design funding incentives to support regular maintenance of artificial reefs and the implementation of sedimentation control measures, to ensure that the ecological function of artificial reefs remains optimal in high-sediment waters.

Further research should focus on evaluating the performance of alternative artificial reef designs with higher structural complexity to be more resilient to sedimentation pressure. Additionally, real-time environmental monitoring systems, such as turbidity sensors and remote underwater cameras, are essential for providing continuous data to support adaptive management. The implementation of IoT-based underwater robots and the integration of multi-optical sensors with machine learning have proven effective in monitoring water quality while simultaneously identifying underwater objects, enabling real-time ecosystem evaluation on a large and dynamic scale [67-69]. These technological advancements reinforce the role of automated sensor-based monitoring, not only in sustainable water resource management but also in enhancing marine conservation efforts through artificial reef supplementation. Comparative studies in various locations of high sediment waters are also recommended to broaden the understanding and develop guidelines for the placement of artificial reefs that are suitable for waters with high sediment pressure and take into account the bottom topography of the waters.

In conclusion, the strategic use of artificial reefs, underpinned by advanced technology and inclusive management approaches, offers a promising avenue for advancing fisheries management objectives. These efforts will not only help sustain biodiversity but also bolster the socio-economic foundations of coastal communities dependent on fishing industries.

AUTHOR CONTRIBUTIONS

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