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Sustainable Management of Coral Reefs and Marine Tourism at Kondang Merak Beach Indonesia

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ABSTRACT

This study assesses the current condition of the coral reef ecosystem, snorkelling tourism suitability, and restoration strategies at Kondang Merak Beach, Indonesia, to support sustainable marine tourism development. Field data were collected using Line Intercept Transect (LIT) surveys, Tourism Suitability Index (TSI) analysis, and carrying capacity evaluation. Results indicate a degraded reef state with an average live coral cover of 11.93%, dominated by massive corals and low fish diversity, classifying the ecosystem as poor. The snorkelling suitability index scored 0.74, indicating very low suitability due to limited coral cover, biodiversity, and reef complexity. Despite ecological limitations, the site can accommodate up to 187 visitors daily across various tourism activities. To address these challenges, a comprehensive five-year integrated management plan is proposed, combining physical restoration (artificial reefs, structural repairs), biological restoration (coral transplantation, reduced human pressure), and spatial zoning enforcement. Sustainable tourism measures such as designated snorkelling paths, visitor education, and no-anchoring zones are recommended to mitigate impacts and enhance reef resilience. This study provides a practical framework for balancing coral reef conservation with ecotourism development and offers insights for managing similarly degraded tropical coastal ecosystems toward sustainable marine ecosystem management. These efforts contribute directly to Sustainable Development Goal 14, supporting the conservation and sustainable use of marine resources.

1. INTRODUCTION

Indonesia, recognized as a maritime nation due to its vast archipelagic geography, has a significant portion of its population residing in coastal regions. Coastal areas, with their abundant natural resources, are crucial to the nation’s economy, providing habitats for diverse ecosystems and offering vast opportunities for sustainable resource utilization [1]. The coastal region of South Malang, located on the southern coast of East Java, exhibits significant biodiversity, with key ecosystems such as mangroves, seagrasses, and coral reefs. These resources generate considerable interest from multiple stakeholders, all of whom seek to either exploit these resources or manage them in accordance with sustainable development principles, emphasizing conservation and responsible tourism management [2, 3].

South Malang's coastal areas maintain rich tropical ecosystems, including mangrove forests often observed along the shoreline. Notable beaches like Balekambang Beach and Kondang Merak Beach are home to flourishing seagrass habitats, while the areas of Sendang Biru, Kondang Merak, and Sempu Island are known for their coral ecosystems. Kondang Merak Beach, in particular, has become a popular destination for tourists, attracting those interested in recreational activities such as snorkelling and diving, as well as researchers exploring marine biota and ecosystems. The area's proximity to protected forests, marine life, and vibrant coral reefs provides significant opportunities for both tourism and research [4-6].

One viable strategy for preserving this rich ecosystem while simultaneously generating economic benefits for the region involves the implementation of a marine ecotourism system. Recent studies have highlighted Kondang Merak Beach's potential for sustainable tourism, with its snorkelling suitability rating at 55.56%, indicating moderate suitability for coral reef-based tourism [7]. However, with increased access to the beach, particularly following the establishment of the Southern Cross Route, there has been a noticeable increase in anthropogenic activities, which have begun to impact the coral reef ecosystem at Kondang Merak Beach. This can interfere with coral recruitment, a key factor in enhancing coral resilience to environmental pressures [8]. These developments underscore the importance of implementing effective management practices to preserve the reef system while fostering tourism development.

As the area's natural beauty and marine ecosystems continue to draw visitors, it becomes essential to assess the current condition of coral reefs and identify marine ecotourism zones using tools such as the Coral Reef-based Tourism Suitability Index (TSI) [9]. This assessment will enable the management of Kondang Merak Beach as a sustainable marine ecotourism destination, balancing ecological preservation with economic growth. Given the complexity of managing such a vital coastal ecosystem, this study seeks to address the research problem of evaluating the current state of the coral reef ecosystem, determining its suitability for tourism, and identifying feasible management strategies to promote its restoration and sustainable use [10].

The primary objective of this study is to assess the coral reef condition at Kondang Merak Beach, evaluate its suitability for sustainable tourism, and propose a comprehensive management framework that integrates both ecological restoration and tourism planning. This research will apply ecological assessments, such as coral cover surveys and fish biodiversity monitoring, alongside socio-economic considerations such as stakeholder involvement and carrying capacity analysis.

The expected contribution of this study is twofold. First, it will offer a practical, evidence-based approach for coral reef restoration and ecotourism development, providing stakeholders with the tools to implement and monitor conservation strategies effectively. Second, the findings will contribute to the broader academic discourse on sustainable marine tourism, serving as a replicable model for other coastal areas facing similar ecological and tourism pressures.

The outcomes of this study will inform future research and policy-making, particularly in relation to sustainable coastal management in tropical ecosystems, aligning with global efforts toward achieving SDG 14 (Life Below Water) [11], specifically Target 14.2 (sustainable management of marine ecosystems) and Target 14.5 (conserving at least 10% of coastal and marine areas).

2. METHODOLOGY

2.1 Study area

The study was conducted from November to December 2020 in the Kondang Merak Beach region, located in Sumberbening Village, Bantur District, Malang Regency, East Java, Indonesia. The research focuses on three designated stations along the coastline, which are marked as Station 1 (green), Station 2 (yellow), and Station 3 (red), as shown in Figure 1.

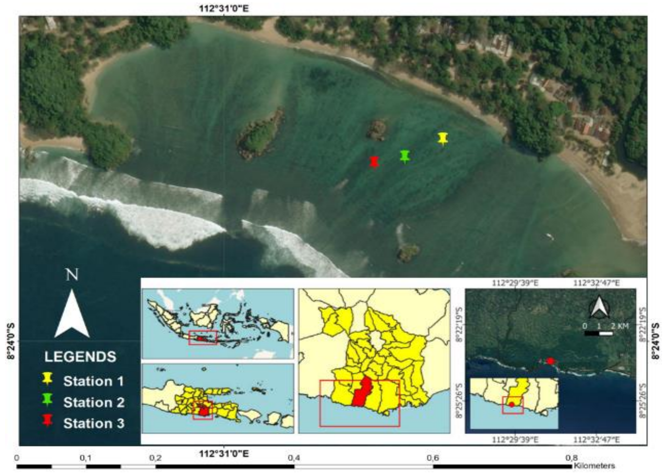

Figure 1. Research location - Kondang Merak Beach

The research stations used for this study remain consistent with those established during the 2013 iteration of the research, enabling a comparative analysis of the state of coral reefs between the two time points. This comparative analysis aims to assess the changes in coral reef conditions over the past decade and contribute to the broader understanding of coral reef resilience in this area.

2.2 Analysis of coral cover percentage

The Line Intercept Transect (LIT) approach, as described by previous study [12], is the measurement technique employed for assessing the proportion of coral reef coverage. The process of data collecting involved the installation of a roll metre of 50 metres in length, with a depth varying between 1.5 and 3 metres. The process of data collecting and recording involved examining the substrate cover in relation to the growth form of coral (life form). The examination of coral reefs involves assessing the percentage of coral cover through the utilisation of the formula proposed by previous study [12].

Reef fish diversity data were collected by direct observation. The observation method uses the visual census method or Visual Census Technique (VCT) - Line Intercept Transect in monitoring or assessing coral fish resources [13].

$$\% \, Coverage = \frac{Total \; length \; of category}{length \; of \; transect} \times 100\% \tag{1}$$

The percentage of live coral cover is then categorized into ecosystem condition assessment criteria using the monitoring guide by Coremap [14]. Based on the percentage of live coral cover, the criteria for assessing coral reef conditions consist of 4 criteria, namely poor/damaged at 0-25%, fair/moderate at 26-50%, good at 51-75%, and very good at 76-100%.

2.3 Water quality suitability analysis

Water quality measurements in this study were carried out by assessing both physical and chemical parameters of the water. The results obtained from these measurements were compared with the established sea water quality standards for marine tourism, as outlined in the Minister of Environment Decree Number 51 of 2004. These standards are presented in Table 1, which serves as a benchmark for evaluating the suitability of the water quality for marine tourism activities.

Table 1. Water quality standards for marine tourism

Parameter	Unit	Standards
Physical		
Depth	m	Not included
Water clarity	m	>6
Temperature	°C	Natural
Odor	-	Odorless
Debris	-	Nil
Oil layer	-	Nil
Chemical		
pH	-	7-8.5
Salinity	%	Natural
Dissolved oxygen	mg/L	>5

2.4 Tourism Suitability Index (TSI) analysis

Suitability analysis is carried out to determine the suitability of the area for tourism. This is based on the region's ability to support tourism activities that can be carried out in the area. The formula used for suitability for snorkelling tourism [15].

$$TSI = \sum_{i=1}^{n} (Bi \times Si) \quad (2)$$

where,

TSI = Tourism index suitability
n = Number of parameters suitability
Bi = i-th parameter weight
Si = i-th parameter score

The calculation of the suitability analysis depends on a number of parameters that serve as supplementary components for the local activities. Every parameter has an evaluation score that is determined by how well it supports the activities that can be performed. On the other hand, the assessment score is a classification derived from field observations. The weight and score are applied to each parameter, and the total of all the parameters' values is the outcome. An area's suitability can be established by comparing its total parameter values, as determined by field observations, with the highest value that is possible, which is presented in Table 2.

Table 2. Suitability category

No	Category	Value	Information
1.	S1	TSI ≥ 2.5	Highly suitable
2.	S2	2.0≤ TSI <2.5	Suitable
3.	S3	1≤ TSI <2.0	Not suitable
4.	N	TSI <1	Highly not suitable

The marine tourism suitability matrix can be seen in Table 3. The suitability of coral reef-based marine tourism is included in the snorkelling tourism category which is arranged based on the importance of each parameter to support snorkelling activities in the research area.

Table 3. Suitability matrix for marine tourism in the snorkelling tourism category

No.	Parameters	Category	Weight	Score
1	Water clarity (%)	100	0.100	3
		80-<100		2
		20-<80		1
		<20		0
2	Coral cover percentage (%)	>75	0.375	3
		>50-75		2
		25-50		1
		<25		0
3	Coral Lifeform	>12	0.145	3
		>7-12		2
		4-7		1
		<4		0
4	Reef fish diversity	>50	0.140	3
		30-50		2
		10-<30		1
		<10		0
5	Current speed (m/dt)	0-0.15	0.070	3
		>0.15-0.3		2
		0.3-0.5		1
		>0.5		0
6	Depth (m)	1-3	0.100	3
		>3-6		2
		>6-10		1
		10		0
7	Width of Coral Expanse (m)	>500	0.070	3
		>100-500		2
		20-100		1
		<20		0

2.5 Analysis of carrying capacity area

For optimal use of marine ecotourism in tourism operations, carrying capacity analyses must be performed in order to maximise the potential of coastal resources, beaches, and small islands. The greatest number of guests that may physically fit in the area at a given moment without disrupting the natural balance or human is known as the carrying capacity area, or CCA. Using the formula, one may calculate the CCA calculation [16].

$$CCA = K \frac{Lp}{Lt} \times \frac{Wt}{Wp} \quad (3)$$

where,

CCA = Carrying capacity area
K = Ecological potential of visitors per unit area
Lp = Area or length of area that can be utilized
Lt = Unit area for a particular category
Wt = Time provided by the area for tourism activities in 1 day
Wp = Time spent by visitors for each particular activity

The area's carrying capacity ought to be modified in accordance with the features of the resource and how it is used. Thus, in order to ensure the sustainability of resources and their ability to be sustained, information regarding their state is required. It is believed that humans want horizontal space to allow them to move around freely and not feel bothered by other visitors, which is presented in Table 4 and Table 5.

Table 4. Ecological potential of visitors (K) and activity area (Lt)

Type of Activity	Σ Visitors (K)	Unit Area (Lt)	Information
Diving	2	2000 m^2	Every 2 people in 100 m × 10 m
Snorkelling	1	500 m^2	Every 1 person in 100 m × 5 m
Seagrass Tourism	1	500 m^2	Every 1 person in 100 m × 5 m
Mangrove Tourism	1	25 m	Calculating the length of the path, each person is 25 m long
Beach Recreation	1	25 m	1 person every 25 m of beach length
Sports Tourism	1	25 m	1 person every 25 m of beach length

Table 5. Time prediction required for each tourist activity

No.	Activities	Time Required (Wp)-hour	Total Time in 1 Day (Wt)-hour
1.	Dive	2	8
2.	Snorkelling	3	6
3.	Swim	2	4
4.	Boating	1	8
5.	Sunbathe	2	4
6.	Beach Recreation	3	6
7.	Water sports	2	4
8.	Fishing	3	6
9.	Mangrove Tourism	2	8
10.	Seagrass Tourism and Other Ecosystems	2	4
11.	Surf Tourism	2	6

2.6 Restoration management strategy analysis

The Restoration Opportunities Assessment Methodology (ROAM), proposed by IUCN and WRI [17], supports coastal ecosystem management by identifying limitations in existing interventions and informing more suitable restoration approaches and locations [18]. ROAM is designed for both operational and policy-making purposes, offering strategic opportunities for ecosystem restoration.

Restoration efforts aim to support natural recovery processes. When these processes fail, alternative management and restoration methods must be employed. Recovery may occur passively—through reduced human pressures—or actively, involving biological or physical interventions. Active biological restoration includes coral transplantation to degraded areas, while physical methods focus on technical repairs, particularly for coral reefs. Ultimately, biological restoration seeks to reestablish ecological functions and species composition.

3. RESULTS AND DISCUSSION

3.1 Water quality suitability

In accordance with the quality standards outlined in the Decree of the Minister of Environment Number 51 of 2004, which pertains to the standards for sea water quality in the context of marine tourism, it can be determined that the water quality at Kondang Merak Beach fulfills the specified criteria. Consequently, the tourist area remains suitable for utilization (Table 6).

Table 6. Water quality suitability in Kondang Merak Beach

No.	Parameters	Quality Standards	Station 1	Station 2	Station 3	Result	Information
1.	Depth (m)	Not listed	1.5	1.9	2.2	1.8	-
2.	Water clarity (m)	>6	1.5	1.9	2.2	1.8	Suitable
3.	Temperature (°C)	Natural	31.3	30.2	29.9	30.4	Suitable
4.	Odor	Odorless	Odorless	Odorless	Odorless	Odorless	Suitable
5.	Rubbish	Nil	-	-	-	-	Suitable
6.	Oil layer	Nil	-	-	-	-	Suitable
7.	pH	7-8.5	8.3	8.3	8.2	8.26	Suitable
8.	Salinity (%)	Natural	34	34	34	34	Suitable
9.	Dissolved oxygen (DO) (mg/L)	>5	9.71	9.71	9.71	9.71	Suitable

3.2 Coral reef condition and substrate composition

The current study reveals that the average live coral cover across three sampling stations at Kondang Merak Beach is only 11.93% (Figure 2A), with individual station values ranging from 10.20% to 13.60%. According to the standard classification, this level of coverage categorized as the "poor" category, indicating degraded reef conditions and limited ecological resilience.

Further analysis of benthic life forms (Figure 2B) shows that the reef is dominated by non-coral substrates. Rubble accounts for the largest proportion at 56.4%, followed by sand (25.8%), and dead coral with algae (5.4%). Live coral forms are present but sparse, consisting mostly of massive corals (10.7%), with minor encrusting (1.1%) and foliose (0.2%) growth forms. These figures reflect a disturbed reef structure with limited complexity and biodiversity. The results of the Kruskal-Wallis statistical test at the three stations showed a significance value of 0.013 (0<0.05) which indicates that there is a significant difference in the results of substrate cover between the three stations.

Historical data further highlight the ongoing degradation of coral reefs at Kondang Merak. In 2009, the live coral cover averaged 27.29%, categorized as "moderate" [19]. By 2013, this value had declined to 23.6%, already considered "poor" [20]. In 2016, recorded coral cover ranged from 0.4% to 26%, with significant damage linked to anthropogenic pressures such as snorkelling, recreational fishing, and trampling by visitors [21]. Meanwhile, in 2019, Kondang Merak Beach's coral reef ecosystem comprised 809 colonies from 28 species (17 genera) with a Shannon-Wiener diversity index of 1.99 (moderate). The reef was dominated by *Oulophyllia bennettae* (34.61%) and *Porites lutea* (31.03%). Most corals in the upper intertidal zone were damaged due to tourist trampling, coral collection, and sedimentation, while the lower intertidal zone retained better cover due to reduced disturbance [4].

This temporal decline underscores the urgent need for targeted coral reef management and rehabilitation efforts. The dominance of rubble and sand substrates suggests past physical disturbances and poor natural recovery, warranting active restoration interventions alongside stronger regulation of tourism and coastal activities.

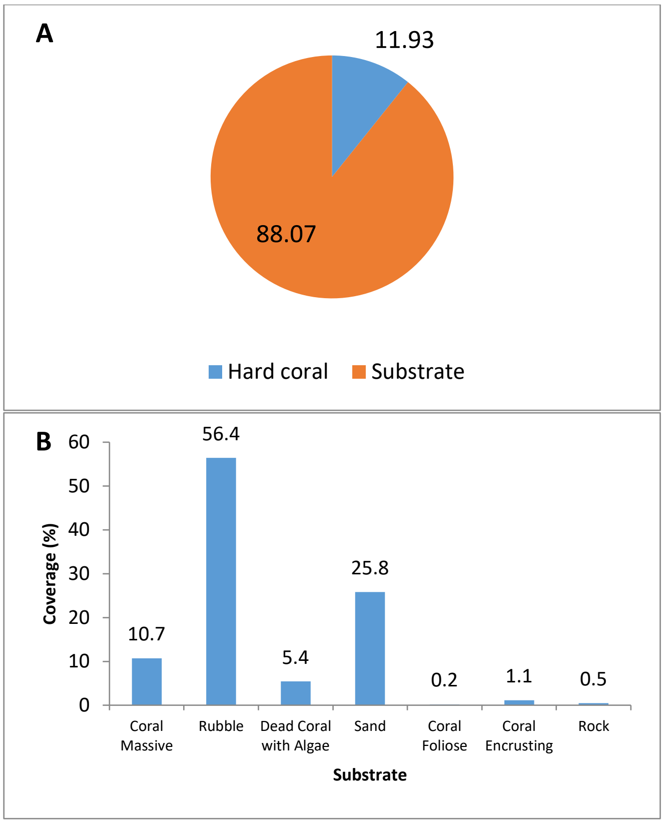

Figure 2. (A) Coral cover percentage; (B) Coral life form
Source: Primary data (2020)

3.3 Snorkelling tourism suitability

An evaluation of the TSI for snorkelling activities at Kondang Merak Beach yielded a score of 0.74, which falls into the "Very Unsuitable (N)" category (Table 7). Despite excellent water clarity (100% suitability), several critical ecological and biophysical parameters limit the site's overall suitability for sustainable marine tourism. Water clarity is uniformly high across the area, primarily due to the gently sloping seabed and minimal anthropogenic pollution [22]. This supports underwater visibility—an essential factor for snorkelling experiences.

However, this strength is offset by ecological limitations, particularly the low live coral cover, which averages 11.93% and is classified as "poor" [14]. Only three coral growth forms were identified—massive, foliose, and encrusting—suggesting low structural diversity. The dominance of coral rubble further underscores the extensive reef degradation in the area.

Table 7. Suitability of marine tourism in the snorkelling tourism category

No.	Parameter	Weight	Category	Score	Weight × Score
1	Water Clarity (%)	0.100	100	3	0.3
2	Coral cover (%)	0.375	<25	0	0
3	Coral *life form*	0.145	<4	0	0
4	Reef fish category	0.140	<10	0	0
5	Current speed (m/s)	0.070	>0.15-0.3	2	0.14
6	Coral depth (m)	0.100	1-3	3	0.3
7	Width of Coral Expanse (m)	0.070	<20	0	0
	Total				**0.74**

Information: Total = weight × score
$TSI = \sum_{i=1}^{n}(Bi \times Si) = 0.74$

A vital aspect of snorkelling enjoyment is the aesthetic and ecological richness of the underwater environment. The limited spatial extent of healthy coral cover reduces horizontal viewing satisfaction, which is crucial for snorkelers [23]. Moreover, the reef fish community is highly depauperate, with only two species observed during the research—*Pomacanthus* sp. and *Chaetodon* sp.—thus weakening the site's attractiveness as a snorkelling destination [24, 25].

Current speeds were measured at an average of 0.18 m/s, classified as weak [26]. This is favorable in terms of tourist safety, as stronger currents could pose a hazard [27]. Additionally, the average depth of coral sites was 1.8 meters during low tide, with high tide depths exceeding 3 meters. These depth conditions fall within the optimal range (1-6 m) for snorkelling [28], contributing positively to the index.

Nonetheless, several parameters scored zero, including coral cover, coral lifeform diversity, fish diversity, and coral expanse width, which are essential for ecological value and tourist appeal. These deficits reflect long-term degradation, possibly due to unregulated tourism and environmental stressors, and represent substantial barriers to the site's ecotourism development.

In conclusion, while Kondang Merak Beach has favorable physical characteristics, such as water clarity and safe depth, the ecological degradation—especially in coral and fish communities—severely undermines its potential for sustainable snorkelling tourism. Strategic restoration and management efforts are urgently needed to improve ecological conditions and enhance the area's tourism suitability.

3.4 Assessment of area carrying capacity for sustainable marine tourism

The concept of carrying capacity plays a vital role in natural resource management by regulating visitor numbers to prevent environmental degradation and ensure long-term ecosystem sustainability [29]. It is a key tool in balancing conservation goals with tourism development, aiming to preserve the ecological integrity of natural assets while supporting the socio-economic well-being of local communities.

At Kondang Merak Beach, carrying capacity was assessed to determine the maximum number of tourists that can be accommodated without compromising the area's environmental quality. The calculation follows the standard methodology considering spatial availability, duration of activities, and ecological thresholds. For snorkelling activities, the following formula was used:

$$Snorkelling : 1\ \frac{1500}{500} \times \frac{6}{3} = 6$$

Extrapolating this across operational periods yields a maximum capacity of 187 individuals per day for all tourism activities at the site.

Tourist use is categorized into two main sectors: beach-based recreation and reef-based activities such as snorkelling and diving. If the number of visitors engaging in reef activities exceeds the carrying capacity (e.g., more than 24 snorkelers at a given time), they are redirected to alternative options such as sport fishing or shoreline leisure. This adaptive management approach ensures that ecosystem pressure is distributed and environmental thresholds are not exceeded.

Integrating carrying capacity into tourism planning provides a quantitative foundation for sustainable visitor management, particularly in ecologically sensitive areas like Kondang Merak. This strategy not only prevents ecological overuse but also enhances visitor experience and satisfaction by avoiding overcrowding and preserving natural aesthetics.

While the current model offers a valuable baseline for estimating visitor capacity, it is important to recognize its simplified assumptions. Specifically, the use of fixed time allocations and uniform spatial distribution across all tourist activities may not accurately reflect real-world dynamics. In practice, tourist behaviour varies considerably in both duration and location preference, potentially resulting in uneven ecological pressure across zones. To address this, future assessments should incorporate sensitivity analyses and spatial variability, such as GIS-based modeling or zonal usage data, to improve the accuracy and ecological relevance of carrying capacity estimates. These refinements will support more responsive and adaptive visitor management in the context of sustainable reef tourism.

3.5 Integrated coral reef restoration framework

Ensuring the ecological sustainability of coral reefs while supporting ecotourism requires a robust and adaptive management strategy. A comprehensive approach that integrates both physical and biological restoration, supported by a structured multi-year management plan, is essential to enhance reef resilience and service quality [29, 30].

3.5.1 Physical restoration

Physical restoration aims to stabilize and reconstruct reef structures that have suffered damage from human activities or natural disturbances. Initial interventions include first aid measures such as the removal of debris, the repositioning of overturned coral colonies, and the application of cement or epoxy to repair fractured coral heads. These emergency responses help reduce further degradation in recently damaged reef areas.

A more structural intervention involves the installation of artificial reefs, which are human-made modules designed to replicate the ecological functions of natural reefs [31]. Artificial reefs enhance habitat complexity, attract reef fish—especially territorial species—and facilitate coral larval settlement [32, 33]. Their placement should be carefully planned to avoid further sedimentation and to maximize hydrodynamic stability.

A compelling example of this approach comes from French Polynesia, where extensive physical restoration was undertaken following sand dredging. Restoration activities included refilling mining pits with 10,000 m² of sand, installing breakwaters, planting beach vegetation, and deploying 125 large concrete modules as artificial reefs near Matira Point. These efforts mitigated shoreline erosion and reestablished sediment dynamics while enhancing habitat availability for reef species [34].

3.5.2 Biological restoration

Biological restoration seeks to reestablish the ecological functionality of coral reefs by improving both biotic and abiotic components. Passive strategies include reducing stressors such as overfishing, sediment runoff, and waste discharge, thereby allowing natural recovery processes to proceed. Active strategies involve direct intervention, such as coral transplantation and the reintroduction of key species [35, 36].

At Bora-Bora's Matira Point, a 7200 m² coral garden was established by transplanting 311 coral colonies onto 111 artificial structures and placing an additional 200 branching (*Acropora spp.*) and massive (*Porites sp.*) corals on the sandbed. Within one year, survival rates exceeded 95%, and fish abundance increased by up to 50%, indicating strong ecosystem recovery [32].

Another success was recorded on Mayotte Island in the Indian Ocean, where reclamation activities threatened coral colonies. A total of 600 colonies were transplanted, achieving an 80% survival rate within a year—demonstrating the effectiveness of proper handling and relocation techniques [37].

In Indonesia, restoration at Damas Beach, Trenggalek, involved the deployment of 25 cube-shaped artificial reefs at a depth of 5-7 meters. After three years, 16 sessile species had colonized the reef modules with a density of 6.94 ind./m², while 26 families of coral reef fish had recolonized the area with a fish density of 1.73 ind./m² [38, 39].

3.5.3 Five-year integrated management plan

Ensuring the long-term success of coral reef restoration and sustainable marine tourism at Kondang Merak Beach necessitates a structured, multi-phase intervention grounded in ecological and social principles. To that end, a five-year integrated management plan has been developed, incorporating physical and biological restoration strategies, community participation, and adaptive monitoring systems, as shown in Table 8. This plan aligns with the principles of ecosystem-based management and supports local governance in coastal conservation [40].

In Year 1, the plan prioritizes ecological stabilization. Physical restoration activities include installing artificial reefs and applying cement or epoxy to damaged coral heads, thereby creating stable substrates for future colonization. Parallel to this, biological restoration begins with baseline ecological assessments to identify degraded reef zones [41] accompanied by the formal establishment of protection zones and no-fishing areas [42]. These early interventions are supported by signage and awareness campaigns aimed at reducing tourism pressure and enforcing marine spatial zoning [43]. Key performance indicators (KPIs) include increased substrate availability and visible enforcement of no-fishing boundaries. This phase is implemented in collaboration with local NGOs, fisher groups, dive operators, and village leaders, who play a central role in site verification, community outreach, and informal surveillance.

Year 2 marks the initiation of active coral rehabilitation, focusing on establishing coral nurseries and implementing transplantation protocols. Site selection is informed by ecological suitability derived from Year 1 assessments. Given the increasing frequency of thermal stress events, coral species known for thermal resilience will be prioritized in transplantation efforts. Biological success is measured by coral nubbin survival rates and nursery growth performance [44]. This phase introduces capacity-building elements by involving youth communities, tourism operators, and local educators in nursery maintenance and transplanting activities, thereby embedding restoration skills in the local social fabric.

Years 3 to 5 are dedicated to maintenance, monitoring, and adaptive management. Artificial structures are cleaned, inspected, and repaired to maintain structural integrity [45]. Simultaneously, biological monitoring is performed annually using Reef Check protocols to track coral cover recovery, species diversity, and fish abundance metrics [46-48]. Universities and marine science students are enlisted as technical partners in data collection, analysis, and interpretation. The Year 5 milestone includes a full reef health evaluation, synthesized in a multi-stakeholder report to inform future planning and identify areas for policy refinement.

Table 8 operationalizes this plan by breaking down activities, indicators, and stakeholder roles for each year. It serves not only as a project roadmap but also as a governance framework—ensuring transparency, accountability, and distributed ownership of conservation outcomes.

Community engagement is not peripheral but central to this approach. Through participatory governance, co-management mechanisms, and local benefit-sharing, communities are empowered to become reef stewards [49]. Their involvement ensures social legitimacy, strengthens compliance, and embeds long-term sustainability beyond the project horizon. Figure 3 complements this strategy by visualizing the timeline of activities, clearly linking technical interventions with social engagement across all five years.

This adaptive, inclusive approach contributes directly to Sustainable Development Goal (SDG) 14, particularly Target 14.2 (sustainably manage and protect marine and coastal ecosystems) and Target 14.5 (conserve at least 10% of coastal and marine areas). Moreover, the Kondang Merak model exemplifies how integrated reef management—when combined with sustainable tourism frameworks—can yield both ecological restoration and local economic revitalization, offering a replicable pathway for coastal resilience in the Global South.

To enhance the effectiveness of the restoration program, the five-year plan is complemented with measurable ecological targets. These include increasing live coral cover from the current 11.93% to at least 25% by year 5 which categorized to moderate, doubling the number of observed reef fish species from 2 to at least 5, and improving reef fish biomass by 50% compared to baseline conditions. These benchmarks provide clear indicators for evaluating ecological recovery and support adaptive management strategies over time.

Table 8. Five-year integrated coral reef restoration and management strategy at Kondang Merak Beach

Year	Physical Restoration	Biological Restoration	Ecological Target	Key Indicators	Stakeholder Involvement
1	• Substrate enhancement for coral attachment • Installation of artificial reefs • Cement/epoxy repairs	• Identify degraded reef zones • Establish protection & no-fishing zones • Reduce tourism impact • Effective zoning implementation	• Baseline ecological data established (e.g., coral cover, fish biomass). • Establish artificial modules based on the degraded zone, reduce rubble cover by 10%	• % substrate availability • No-fishing signage installed	• Local NGOs • Dive operators • Fisher groups • Village leaders
2	Site selection for reef deployment	• Coral nursery establishment • Coral transplantation by selecting of bleaching-resilient coral species	• 70% survival rate of coral nubbins after 6 months • Coral nursery sites achieve ≥50% growth success of coral fragments	% survival of coral nubbins	• Youth community • Tourism associations
3	Maintenance of artificial structures	Reef Check monitoring	• Coral cover increases by ≥10% compared to Year 1 baseline. • All artificial structures remain intact and colonized by benthic fauna. • Recording 3 reef fish species	% increase in coral cover	• Universities • Marine science students
4	Continued maintenance	Ongoing Reef Check	• Fish biomass increases by ≥20% compared to baseline. • Key indicator fish species observed in restored zone • Coral cover reach ≥20%	Fish abundance metrics	Trained local rangers
5	Continued maintenance	Final Reef Check & evaluation report	• Coral cover ≥25%, ≥5 reef fish species, biomass +50% • Biodiversity index (Shannon or Simpson) improves by ≥15% from baseline.	Ecosystem health index score	• Multi-stakeholder taskforce • Community reporting units

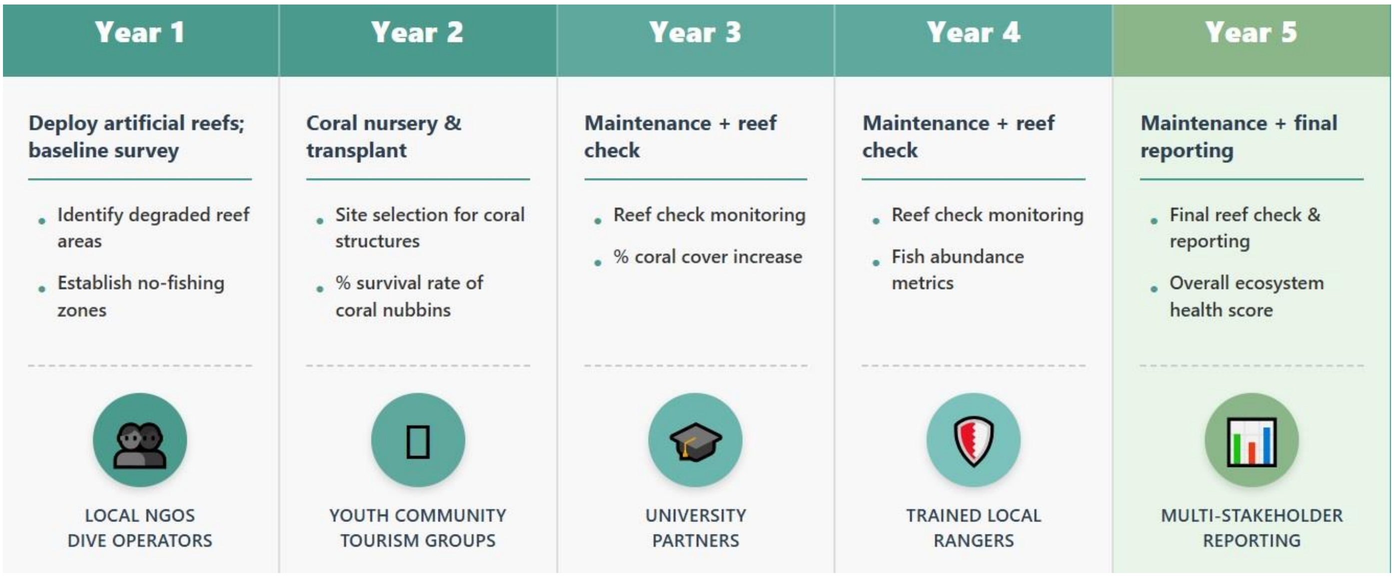

Figure 3. Timeline of coral reef restoration at Kondang Merak Beach, integrating ecological actions and community roles over five years

3.6 Sustainable tourism development strategy at Kondang Merak Beach

Implementing snorkelling guidelines that minimize the impact on coral reefs involves a multi-faceted approach, primarily focusing on educating snorkelers about the ecological importance of coral ecosystems and their vulnerability. Essential to this strategy is the establishment of designated snorkelling paths, marked clearly to guide snorkelers away from sensitive coral areas, thereby reducing direct contact and potential damage [50]. These paths, outlined with buoys and floating signage, provide a visual reminder of the need to maintain a safe distance from the coral, emphasizing practices such as buoyancy control to avoid touching or standing on the reef [51].

To further mitigate impact, access to coral areas is restricted, limiting the number of snorkelers at any given time to prevent overcrowding. Enforcement of no-anchoring zones around coral reefs helps to prevent physical damage from boat anchors [52]. Implementing measures to prevent physical damage from boat anchors has a positive effect on protecting coral reefs [53].

To ensure adherence to these guidelines, trained guides or marine park rangers supervise snorkelling activities [54], with penalties established for non-compliance. This comprehensive approach not only safeguards coral ecosystems but also enhances the snorkelling experience, ensuring the sustainability of marine tourism by preserving the beauty and biodiversity of coral reefs for future generations [55].

Enforcing such guidelines fosters responsible behaviour among tourists and supports ecosystem resilience. Previous studies emphasize the importance of integrated management strategies in balancing coral conservation with sustainable tourism [14], while recreational activities like snorkelling have been shown to impact benthic community structures, reinforcing the need for protective measures [56].

Educational programs further improve conservation outcomes by promoting environmental stewardship among visitors [57]. Ultimately, structured management enhances both ecological integrity and tourist satisfaction, as demonstrated in recent findings [3, 58].

Setting carrying capacity limits for snorkelling is essential to prevent overcrowding and reduce human impact on coral reefs. This involves defining the maximum number of visitors a site can accommodate without causing significant ecological harm [59]. Enforcing these limits enables sustainable snorkelling practices, safeguarding reefs for future generations while maintaining tourist enjoyment [60]. Beyond protecting corals from damage and stress, it also enhances visitor experiences by preventing issues like poor water clarity and fewer wildlife sightings [61].

Tourism development strategies should be tailored to the unique goals of each destination, identifying key features and processes to enhance decision-making and management effectiveness [62, 63]. Strengthening community participation, improving visitor education, and adopting conservation-based tourism models can bolster marine ecosystem resilience and generate local economic benefits [64]. In Kondang Merak, ecology-based tourism—such as diving and snorkelling—offers opportunities for rural economic growth, improved living standards, job creation, infrastructure development, and the preservation of cultural traditions.

4. CONCLUSION

This study reveals that the coral reef ecosystem at Kondang Merak Beach is currently in a degraded state, characterized by a low average live coral cover of 11.93%, which is classified as "poor" according to national reef health standards. The reef is dominated by massive coral forms with limited diversity in coral life forms and a seabed mostly composed of rubble and sand. Reef fish diversity is notably low, reducing both the ecological functionality and aesthetic value of the site for marine tourism purposes.

The TSI for snorkelling indicates that the area is very unsuitable for sustainable snorkelling activities, with a score of 0.74. The principal limiting factors include insufficient coral cover, low fish biodiversity, fragmented reef structure, and limited horizontal coral expanse. Despite these ecological constraints, the area has the physical capacity to accommodate up to 187 visitors per day, provided that appropriate environmental regulations and visitor management strategies are implemented.

To address these challenges, a comprehensive five-year integrated management plan is proposed, combining physical restoration efforts (such as artificial reef deployment and structural repairs), biological restoration (including coral transplantation and reduction of anthropogenic pressures), and spatial zoning enforcement. In addition, sustainable tourism strategies—such as designated snorkelling paths, visitor education, no-anchoring zones, and controlled visitor numbers—are essential to mitigate human impacts and support reef resilience.

This study is limited by its relatively short observation period and focus on a limited set of biophysical indicators. Although the field survey was limited to a single period (Nov-Dec 2020), long-term degradation trends are inferred through comparison with prior studies conducted in 2009, 2013, and 2016, acknowledging the need for continuous monitoring to confirm these trajectories. Future research should emphasize long-term ecological monitoring, assessment of climate change vulnerability, and the incorporation of participatory governance involving local communities. Such integrated approaches are critical to achieving sustainable marine tourism and effective coral reef conservation in tropical coastal ecosystems facing increasing anthropogenic and environmental pressures. In addition to local management actions, climate change mitigation and adaptation measures such as incorporating bleaching-resilient coral species, should be integrated into future restoration efforts to enhance long-term ecological resilience.

Importantly, these efforts contribute directly to the achievement of Sustainable Development Goal 14 (Life Below Water), particularly Target 14.2, which promotes sustainable management and protection of marine and coastal ecosystems, and Target 14.5, which calls for the conservation of at least 10% of coastal and marine areas. This alignment underscores the broader significance of the study's integrated restoration and tourism management framework as a model for sustainable coastal development.

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