INTERNATIONAL JOURNAL OF CONSERVATION SCIENCE

ISSN: 2067-533X Volume 17, Issue 1, 2026: 391-410 www. ijcs. ro

DOI: 10. 36868/IJCS.2026.01.24

CORAL REEF ECOSYSTEM MANAGEMENT MODEL BASED ON INTEGRATED COASTAL MANAGEMENT (ICM) (CASE STUDY OF THE COASTAL AREA OF PALOPO CITY)

Muhammad BIBIN[1,*], Herman DEMA[2], DAMIS[1], Jamaluddin AHMAD[3], Ani ARDIAN[3]

[1] Fisheries Science Study Program, Faculty of Science and Technology, University of Muhammadiyah Sidenreng Rappang, Lt. Salo – Rappang, Indonesia, 91651

[2] Government Science Study Program, Faculty of Social and Political Sciences, University of Muhammadiyah Sidenreng Rappang, Lt. Salo – Rappang, Indonesia, 91651

[3] Public Administration Study Program, Faculty of Social and Political Sciences, University of Muhammadiyah Sidenreng Rappang, Lt. Salo – Rappang, Indonesia, 91651

Abstract

The degradation of coral reefs off Palopo City's shore would jeopardize its productivity. Consequently, it is imperative to employ and oversee coral reef ecosystems along the coast of Palopo City by implementing the principles of the conservation area management system through integration, participation, and multi-stakeholder involvement. This study seeks to find and examine integrated coastal management (ICM) models for coral reef ecosystem management applicable to Palopo City. Additionally, offering suggestions for enhancing the sustainable management of coral reef ecosystems. This study was performed in the coastal region of Palopo City, South Sulawesi Province, employing coral reef condition analysis and dynamic model analysis for data evaluation. The predominant life form is Acropora branching (ACB), with 218 colonies. Coral organisms serve as a primary benchmark for evaluating the current state of coral reef ecosystems. The coral cover percentage along the shore of Palopo City ranges from 0% to 15% and is classified as damaged or in bad condition. One contributing factor to coral reef degradation in the coastal region of Palopo City is the fishing community's historical practices, including the use of explosives for fishing. This is evidenced by the elevated percentage of dead corals, ranging from 65.46% to 84.6%. The simulation results indicate that the primary method for managing coral reef ecosystems in the coastal region of Palopo City is the implementation of Integrated Coastal Zone Management (ICZM), which has the potential to enhance coral cover by up to 35%. The secondary plan involves establishing local laws for marine tourist operations aimed at enhancing coral cover by 20%. The third option involves establishing coastal and marine conservation organizations. This method can enhance coral reef coverage in the waters of Palopo City by around 15%.

Keywords: *Colony Size Distribution; Coral Reef Ecology; Conservation; Palopo City; Policy*

Introduction

The coral reef ecosystem is crucial for maintaining the biological equilibrium of the ocean. Coral reef ecosystems possess a highly intricate trophic structure, serving as habitats for many fish species, mollusks, and echinoderms [1]. The advantages provided by coral reefs are

* Corresponding author: muhammad.bibin01@gmail.com

categorized into two types: direct benefits and indirect benefits. Direct advantages include industrial applications and the provision of raw materials for construction. Generates diverse fish resources, with indirect advantages such as safeguarding beaches from erosion, mitigating wave impact, and serving as a natural resource that sustains coastal towns [2], [3].

Palopo City encompasses a water area of 172 and features a coastline measuring 21. The coral reef region in the waters of Palopo City is 16 hectares and consists of bordering reefs (Palopo City Fisheries Service 2024). The viability of the coral reef ecosystem ensures the sustainability of capture fisheries and tourism in the coastal regions of Palopo City; therefore, it is essential to investigate management strategies for the coral reef ecosystem to support capture fisheries and the marine tourism sector sustainably.

The state of coral reefs in the waters near Palopo City is a growing concern due to multiple factors, including pollution and poorly managed human activities, such as damaging fishing practices. From 2009 to 2013, traditional fishermen utilized fish bombs and potassium in the seas surrounding Palopo City. This aligns with the findings of [4], which indicate that traditional fishing methods impact the sustainability of coral reefs, as observed at Kei Besar Island, Southeast Maluku. In addition, anthropogenic disturbances, including sedimentation, transpire in Bone Bay [4].

Sustainable management of coral reef ecosystems is crucial for addressing the issues faced by the coral reef ecosystem in the waters of Palopo City. A worldwide implemented strategy for the effective management of coastal and marine ecosystems is Integrated Coastal Management (ICM), or integrated coastal area management. Integrated Coastal Management (ICM) is a methodology that prioritizes comprehensive stewardship of coastal regions, engaging multiple stakeholders, including governmental bodies, local communities, the tourism industry, and non-governmental organizations (NGOs). This methodology seeks to attain an equilibrium between development and environmental conservation [5], [6].

The examination of the ICM-based coral reef ecosystem management model in the coastal region of Palopo City is crucial, given that the presence of coral reefs in this area is essential for the sustenance of fishing communities and the marine tourism sector. Nonetheless, the implementation of Integrated Coastal Management (ICM) in coastal and marine regions of Palopo City remains nascent and encounters numerous challenges, including inadequate inter-institutional coordination, a scarcity of personnel knowledgeable in coral reef ecology, and a low level of awareness among coastal communities regarding the significance of preserving coral reef ecosystems. This project seeks to discover and analyze integrated coastal management (ICM) models for coral reef ecosystem management applicable to Palopo City. This project will evaluate the efficacy of current regulations and offer ideas for enhancing the sustainable management of coral reef ecosystems.

Research Methods

This study was conducted in Palopo City, South Sulawesi Province. The research occurred from June to November 2024. This study utilized two categories of data: main data and secondary data. Primary data was acquired by field observations, encompassing both physical assessments and interviews with various stakeholders regarding the management, development, and utilization of coastal areas. Concurrently, secondary data was acquired through questionnaires and literature reviews from verified data sources provided by various institutions and governmental bodies.

Data Collection Techniques

The methodologies employed for data collection to enhance data analysis and discourse are as follows:

1. Biophysical Dimensions
   a. Hydrological Integrity

      The acquisition of water quality data is conducted with multiparameter measuring devices for water quality testing. The observed water quality parameters are temperature, salinity, pH, and turbidity. Water quality metrics were measured at sampling sites to assess coral and reef fish conditions. Water quality data is obtained by interpreting the readings displayed by the instrument.

   b. State of Coral Reefs

      The technique for assessing the status of coral reefs involves the utilization of underwater photo transect (UPT) methodology.

   c. Coral Fish

      Coral fish were observed utilizing the underwater visual census (UVC) methodology.

2. Socioeconomic Information

The data collection method employs comprehensive interviews with informants. This technique is employed to gather information regarding the management of coral reef waters, as well as the socioeconomic and cultural conditions prevalent in the management of Palopo City's waters. Additionally, it is utilized to examine the historical management of coral reefs and fishery resources, gauge community perspectives on traditional institutions, and gather data on the efficacy of coral reef ecosystem management and water conservation efforts. The chosen informants comprised stakeholders involved in the management of coral reef ecosystems in the waters of Palopo City, including community organizations, religious leaders, traditional leaders, city government officials, non-governmental organization (NGO) activists, and academics.

Data Analysis

The assessment of hard coral cover is based on the methodology outlined by [7] (formula 1), while the categorization of frequency classes in coral follows the approach of [8], which involves sorting from the smallest class (0-4 cm²) to the most significant class (>4000 cm²).

$$P = \frac{a}{A} x \ 100\% \qquad (1)$$

where: P - Percentage of coral cover; a - The area of a particular type of coral; A - Total transect area.

Data on the results of hard coral cover categorized according to the Decree of the Minister of the Environment Number 4 of 2001 are presented in Table 1.

Table 1. Coral Cover Condition Categories

Category	Percentage of Live Coral Cover
Damaged/bad	0 – 24,9%
Currently	25 – 49,9%
Good	50 – 74,9%
Very good	75 – 100 %

Source: (MENLH, 2001)

Categories of coral growth forms and other substrates are presented in Table 2.

Table 2. Forms of coral growth and other substrates

Category		Code	Information
Dead coral		**DC**	Newly dead coral is white
Dead coral with algae		**DCA**	Dead coral overgrown with algae
Hard coral:			
Acropora: *Branching*		**ACB**	Forked like a twig. Example *A. formosa, A. palmata*
	Encrusting	**ACE**	Creeping form like rudimentary acropora. Example *The Cuneata*
	Submassive	**ACS**	Plate-branched and sturdy. Example *A. palifera*
	Type	**ACD**	The branches are close together like the fingers of a hand. Example *A. digitifera*, *A. humble*
	Tabulate	**ACT**	Horizontal branching. Example *A. blue*
Non Acropora:	*Branching*	**CB**	Branches like tree branches. Example *Seriatopura hystrix*
	Encrusting	**THIS**	Creeping form, attached to the substrate. Example *Montipora undata*
	Foliose	**CF**	The shape resembles a sheet. Example *Merulin expanded*
	Massive	**CM**	Shaped like a large stone. Example *platygyra deadalea*
	Submassive	**CS**	Sturdy shape with ridges. Example *Porites lichen*
	Mushroom	**CMR**	Shaped like a mushroom, solitary. Example *Close the repanda*
	Millepora	**CME**	All types of fire coral have a yellow color at the end of the colony
	Heliopora	**CHL**	Blue coral, the presence of blue on the skeleton
Other Fauna			
Soft Coral		**SC**	Coral with a soft body
Sponge		**SP**	Examples like *Aaptos aaptos*
Zoanthids		**LIKE THIS**	Examples like *Palythoa tuberculosa*
Others:		**OT**	Anemone, water lily, gorgonian, chimney
Algae: *Assemblage*	*Algae*	**AA**	Consists of more than one algae
Algae	*Coralline*	**THAT**	Algae that have a chalky structure
	Halimeda	**HA**	Algae of the genus *Halimeda*
	Macroalgae	**AND**	Algae are large
	Turf Algae	**FACING**	Resembles fine grass
Abiotic:	*Sand*	**S**	Sand
	Rubble	**R**	Scattered coral fractures
	Silt	**AND**	mud
	Water	**WA**	Water column/gap with a depth of more than 50 cm
	Rock	**RCK**	Coral step
Other		**DDD**	Data not recorded or lost

Dynamic Model Evaluation

To develop a coral reef ecosystem management model for the waters of Palopo City, it is essential to gather information regarding the characteristics of the coral reef ecosystem, including the factors contributing to the decline in live coral cover, both natural and anthropogenic, as well as the socioeconomic, cultural, and institutional conditions of the local communities. Additionally, the development of a dynamic model for coral reef ecosystem management in the waters of Palopo City requires the following information in Figure 1.

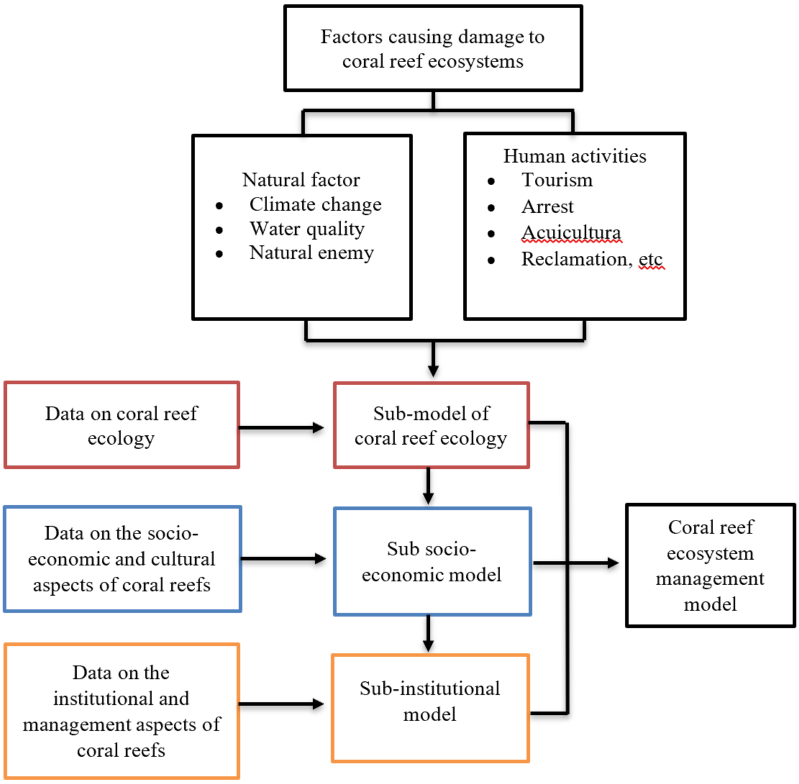


Fig. 1. Identification of information needs to build a system

Results and Discussion

State of Coral Reefs in the Waters of Palopo City

Organism Eight coral species are identified in the observation sites in the waters of Palopo City, including *Acropora digitate* (ACD), which comprises 84 colonies distributed as follows: at station 1, there are 10 colonies at a depth of 3 meters and 19 colonies at a depth of 10 meters. At a depth of 3 meters at station 2, there are two colonies, and at a depth of 10 meters, there are eight colonies. At a depth of 3 meters at station 3, there are 33 colonies, whereas at a depth of 10 meters, there are 22 colonies. *Coral foliose* (CF) comprises 114 colonies distributed as follows: at station 1, there are 15 colonies at a depth of 3 meters and 32 colonies at a depth of 10 meters. No life forms were detected at station 2; however, at station 3, 14 colonies were identified at a depth of 3 meters, and 53 colonies were observed at a depth of 10 meters. *Coral mushroom* (CMR) comprises 30 colonies distributed as follows: at station 1, 2 colonies are located at a depth of 3 meters, and one colony is situated at a depth of 10 meters. At station 2, no coral development was observed at depths of 3 and 10 meters. Conversely, at station 3, there is one colony at a depth of 3 meters and 26 colonies at a depth of 10 meters. *Acropora* branching (ACB) identified 162 colonies, distributed as follows: at station 1, 27 colonies were located at a depth of 3 meters, and 18 colonies were found at a depth of 10 meters. At station 2, at a depth of 3 meters, two colonies were observed; however, at 10 meters, no life forms were detected. At a depth of 3 meters in station 3, there are 44 colonies, whereas at a depth of 10 meters, there are 71 colonies. *Millepora* coral (CME) identified 40 colonies distributed as follows: at station 1, 3 colonies were located at a depth of 3 meters, and 12 colonies were found at a depth of 10 meters. At station 2, at a depth of 3 meters, no coral development was seen; however, at 10 meters, one colony was present. At a depth of 3 meters in station 3, there are 16 colonies, whereas at a depth of 10 meters, there are eight colonies. *Coral encrusting* (CE) of 125 colonies is distributed as follows: at station 1, there are 15 colonies at a depth of 3 meters and seven colonies at a depth of 10 meters. At a depth of 3 meters in station 2, there are three colonies, and at a depth of 10 meters, there are six colonies. At a depth of 3 meters at station 3, there are 38 colonies, whereas at a depth of 10 meters, there are 56 colonies. *Coral branching* (CB) comprises 129 colonies distributed as follows: 2 colonies are located at station 1 at a depth of 3 meters and 12 at a depth of 10 meters. At station 2, a depth of 3 meters yielded one colony, whereas no coral growth was observed at 10 meters. At a depth of 3 meters at station 3, there are 89 colonies, whereas at a depth of 10 meters, there are 25 colonies. *Coral massive* (CM) comprises 63 colonies distributed as follows: at station 1, there are three colonies at a depth of 3 meters and one at a depth of 10 meters. No coral development was seen at station 2; however, at station 3, two colonies were present at a depth of 3 meters and 57 colonies at a depth of 10 meters.

The growth form of coral can yield distinct insights into the state of the aquatic environment in a given area [9], [10], [11]. Classifies the relationship between coral growth forms and the surrounding aquatic environment: first, ruderals (r), corals that readily adapt to their environment or quickly recover from damage, exemplified by Acropora species, known for their rapid growth yet susceptibility to breakage. The two competitors (K) are non-coral *Acropora* species, specifically foliose and branching forms, dominating aquatic environments and exhibiting rapid development. The third category is coral, namely massive and submassive corals, which can mitigate stress, functioning as stress tolerators by withstanding sedimentation and eutrophication in aquatic environments.

Refer to Table 3 regarding corals; *Acropora* branching, resembling twigs, is frequently located at station 3. Station 3 exhibits robust currents, resulting in the predominance of this specific variety of *Acropora* in the area. The branched structure of *Acropora* mitigates the effects of powerful waves and ocean currents by dispersing the force across the structure, hence reducing the likelihood of fractures in the coral branches [12], [13]. Conversely, station 3, specifically stations 1 and 2, is characterized by sheet-like coral (CF), branching coral resembling tree branches (CB), and creeping coral affixed to the substrate (CE). Regarding layout, these two stations are situated near the port and fish landing base (PPI), which is characterized by a relatively high density, indicating their closeness to the source stressors such as pollution and fishing activity. The source of the stressor is silt originating from river mouths near the observation station. Sediment significantly influences coral reefs, impacting the health and sustainability of these ecosystems. Sediment can alter the structure of coral reef habitats by modifying the content and distribution of resident species [14], [15]. Sediment can diminish sunlight penetration in aquatic environments, disrupting coral symbionts' photosynthetic processes [16]. The predominant sheet-like coral (CF) at station 1 is *Merulina ampliata*. The coral encrusting (CE) identified at station 2 is *Leptastrea transversa*. These two coral varieties are classified as K and S due to their significant capacity to adapt to sedimentation, specifically by secreting mucus that obstructs sediment from infiltrating their polyps [17]. The *Merulina* coral exhibits a colony morphology characterized by a branching structure that facilitates load distribution and mitigates damage from robust ocean currents or shifting sediments. This structure facilitates the efficient acquisition of sunlight, essential for symbiotic photosynthesis. Similar to numerous other corals. In contrast, the morphology of the coral species *Leptastrea transversa*, which often exhibits a rounded form, diminishes silt buildup on the colony's surface relative to foliose corals.

Table 3. *Life form* found at each research station

No	*Life form* coral	Station						Amount
		ST 1		ST 2		ST 3		
		3 m	10 m	3 m	10 m	3 m	10 m	
1	ACD	10	19	0	0	33	22	84
2	CF	15	32	0	0	14	53	114
3	CMR	2	1	0	0	1	26	30
4	ACB	27	18	0	0	21	71	137
5	CME	3	12	0	0	16	8	39
6	THIS	15	7	0	0	11	56	89
7	CB	2	12	0	0	25	89	128
8	CM	3	1	0	0	2	57	63

Description: ST: Research Station; ACD: *Acropora digitate;* CF: *Coral foliose*; CMR: *Coral mushroom*; ACB: *Acropora branching*; CME: *Millepora coral*; THIS: *Coral encrusting*; CB: *Coral branching*; CM: *Coral massive.*

The proportion of living coral coverage in the seas of Palopo City varies between 0.65% and 15%. The status of coral reefs in the waters of Palopo City is classified as damaged or poor, according to the Decree of the State Minister for the Environment Number 4 of 2001 about Standard Criteria for Coral Reef Damage [18]. The frequency distribution of hard corals according to their growth form spans a limited range from 0 to 4 cm² to over 4000 cm², including forms such as branched Acropora, densely branched Acropora resembling fingers, non-coral branched Acropora, and leaf-shaped corals (Table 4 and Fig. 2). The graph depicted in figure 2 will generally exhibit a bell shape with leftward skewness. This distribution features elongated tails or additional data on the left side of the bell curve, indicating the presence of lower extreme values. The right side of the curve is more pronounced. Left skewness signifies that the median exceeds the mean.

Table 4. Water bottom cover of Palopo City (%)

No	Cover Type	Station Name					
		ST 1		ST 2		ST 3	
		3 m	10 m	3 m	10 m	3 m	10 m
1	Life coral	0.65	2.10	0	0	10.37	15
2	Dead coral	84.06	74.23	72.53	67.16	80.03	65.46
3	Algae	0.11	0.13	0	0	0	0
4	Abiotic	15.16	23.53	27.16	32.43	8.78	19.13
5	Other*	0	0	0.3	0.40	0.80	0.40

Remarks (*): Other (OT): Marine biota that is not included in the calculation category

Diverse conditions seemingly affect the proportion of living coral cover. Table 4 indicates that the hard coral cover at station 1 is 0.65% at a depth of 3 meters and 2.10% at a depth of 10 meters. Similarly, at station 3, the hard coral cover is 10.37% at a depth of 3 meters and 15% at a depth of 10 meters. The proportion of deceased coral in the waters of Palopo City is significantly high, ranging from 65.4% to 84.06% (Table 4).

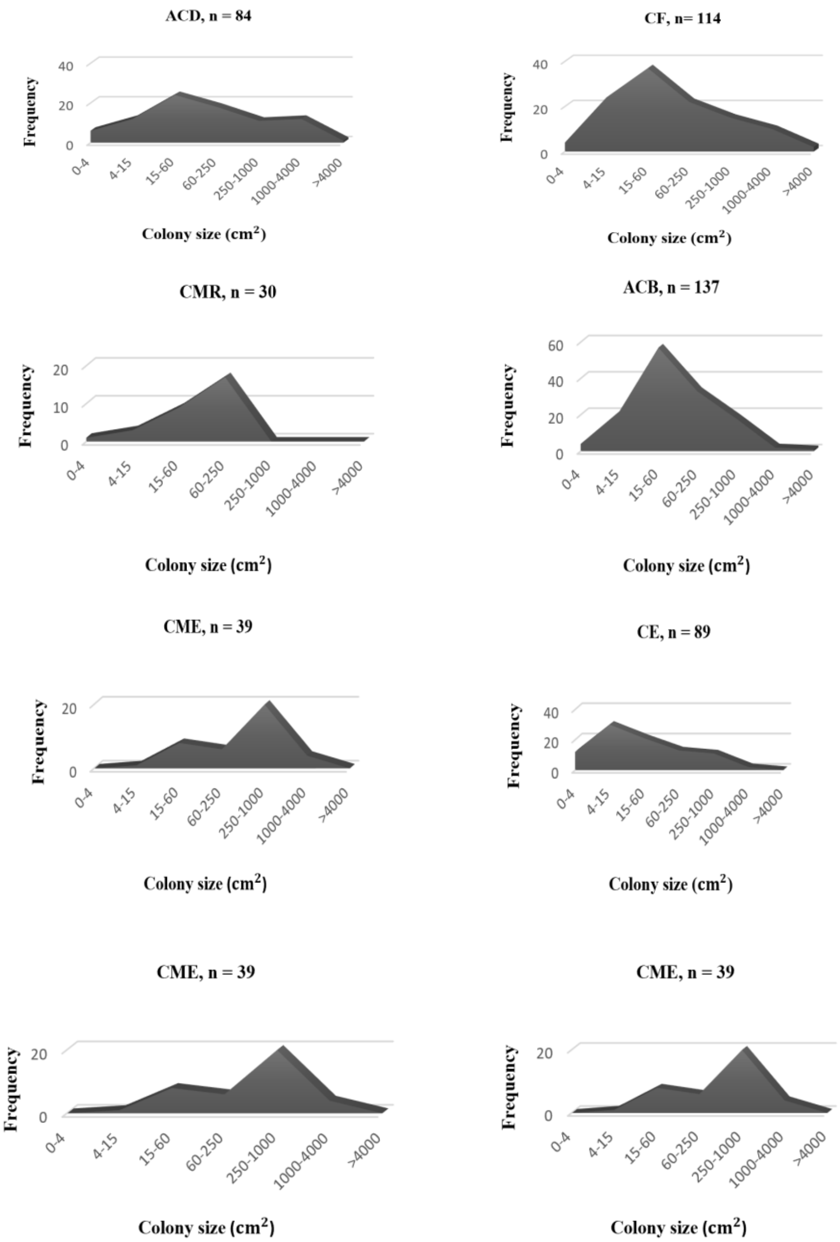


Fig. 2. Size distribution of hard corals found in Palopo City Waters

The elevated proportion of deceased coral is attributable to several primary reasons persistently occurring [19], [20]. Field observations indicate multiple stressors or risks contributing to elevated coral death, including sedimentation, increasing sea temperatures, tourism activities, and harmful fishing practices, such as using explosives and potash. Coral reef degradation due to these variables transpires in other marine regions of Indonesia, as indicated by the research of [21] and [22], which shows that the primary reasons contributing to the elevated mortality of corals in Indonesia's coastal and marine regions include tourism activities, sedimentation, and the escalation of explosive fishing practices. Coastal coral reefs face a heightened risk compared to those situated in remote island regions, distanced from primary activity. [23] and [24] indicated that the effects of the mainland on coral reef existence encompass disruption of reproductive systems and recruitment patterns, diminished growth and recovery capabilities, heightened competition from algae and sponges, increased disease prevalence in corals, and elevated coral mortality rates. According to the data in Table 2, the reduction of live coral resulting from environmental stress will elevate the proportion of coral mortality in the seas of Palopo City. It could augment the population of coral competitors in that region.

Frequency Distribution

The area of coral colonies is optimal for assessing the health of coral reefs by evaluating the proportion of live coral cover within a designated water region corresponding to the area of the conducted transect. Additional information is derived from the colony area through the analysis of the frequency distribution of the colony area. Figure 1 illustrates the diverse sizes of coral colonies, which can be classified as tiny (juvenile) colonies measuring less than 100 cm², medium colonies (puberty) beyond 100 cm², and big colonies above 4000 cm² [25], [26]. Despite theoretical disruptions in the reproduction and recruitment processes of corals in Palopo City's waters due to environmental pressures, Figure 1 indicates that the population of tiny colonies (juveniles) and medium colonies (pubescent) predominates over that of giant corals. This indicates that environmental stress is not constant in the waters of Palopo City; at certain times, environmental conditions facilitate coral recovery. The currents swiftly remove sediment-contaminated coral mucus, preventing anoxia and localized bleaching on the surface of coral colonies. Currents spread coral's natural food, specifically plankton, and maintain seawater temperature, ensuring stability [27], [28]. The population of giant corals in the waters of Palopo City is minimal, likely due to human extraction or natural degradation. At least 100 species of bioeroders inhabit coral masses, accelerating the fragmentation of coral into smaller colonies.

Parameters of Sea Water Quality

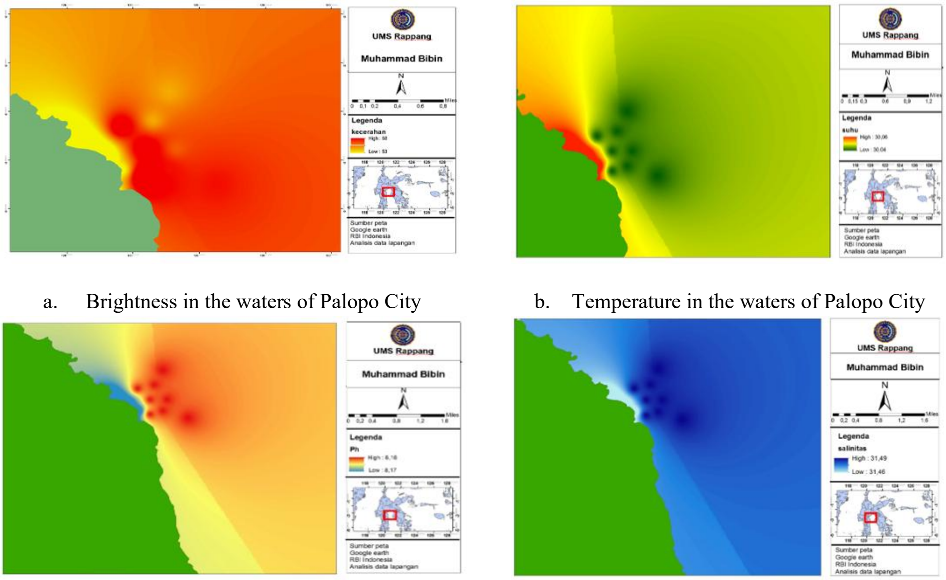
Many physical and chemical water quality indicators assess the water conditions in Palopo City. The assessment of physical and chemical parameters and comparisons to water quality requirements outlined in [29] serve as the foundation for directing water management strategies. The factors assessed in this study are only confined to those directly associated with coral reefs. The parameters of seawater quality in Palopo City are presented in Table 5.

Table 5. Sea water quality parameters in Palopo City

Parameter	Station 1		Station 2		Station 3	
	3–6 meters	7–10 meters	3–6 meters	7–10 meters	3–6 meters	7–10 meters
humidity (ºC)	30	30	30	30	30	30
Brightness (%)	79	65	80	69	89	73
Current speed	0.14	0.18	0.14	0.18	0.16	0.21
Ph	8	8	8	8	8	8
Salinity	31	31	31	31	31	31

Source: processed primary data 2024

The luminosity of the waters is a critical factor in the suitability index for diving and snorkeling tourism, carrying the most tremendous significance [30]. Observations at the research site indicated water brightness at depths of 3 to 6 m: 79% at station 1, 80% at station 2, and 89% at station 3. The observational results at the research site indicated water brightness at depths between 7 and 10 meters. At station 1, the brightness attained 65%; at station 2, it reached 69%; and at station 3, it achieved 73% (Fig. 3a). This condition is within the category appropriate for diving and snorkeling tourism. [29] stipulates that the suitable brightness for marine tourism exceeds 3 m. The water temperature at stations 1, 2, and 3 is around 30ºC (Fig. 3b). According to [29], water temperature is a crucial determinant of coral life. Coral reefs thrive optimally at temperatures ranging from 25ºC to 29ºC, can endure a minimum temperature of 15ºC, and withstand a maximum temperature of 36ºC. The salinity of the waters in Palopo City is around 31‰ (Fig. 3b). [31] indicate that coral reefs often thrive at a salinity of 30‰–35‰ in coastal regions. Although coral reefs may endure saline levels beyond this range, their growth will be impeded relative to waters with standard salinity. The impact of salinity on coral significantly fluctuates based on local seawater conditions and other environmental factors.



a. Brightness in the waters of Palopo City

b. Temperature in the waters of Palopo City

c. Ph in the waters of Palopo City

d. Salinity in the waters of Palopo City

Fig. 3. Palopo City Water Quality

The velocity in the slow category waters of Palopo City varies between 0.14 and 0.21 m/s (Fig. 3d). [32] categorizes currents as follows: slow currents range from 0 to 0.25 m/s, medium currents from 0.25 to 0.50 m/s, fast currents from 0.25 to 1 m/s, and swift currents exceed 1 m/s. Water quality assessments in Palopo City indicated an acidity (pH) range of approximately 8 (Figure 3c). According to [29], the optimal pH for marine biota is between 7 and 8.5. The results demonstrate that the seas of Palopo City remain pristine, as there is no evidence of ocean acidification. The present velocity in the slow category waters of Palopo City varies between 0.14 and 0.21 m/s (Fig. 3d). [33] categorizes currents as follows: slow currents range from 0 to 0.25 m/s, medium currents from 0.25 to 0.50 m/s, fast currents from 0.25 to 1 m/s, and very fast currents exceed 1 m/s. Water quality assessments in Palopo City indicated an acidity (pH) range of approximately 8 (Fig. 3c). According to [29], the optimal pH for marine biota is between 7 and

8.5. The results demonstrate that the seas of Palopo City remain pristine, as there is no evidence of ocean acidification.

Management of coral reefs in Palopo City According to Current Circumstances

Coral reefs are vital marine ecosystems that significantly contribute to marine biodiversity, uphold ecological equilibrium, and sustain the economy through fishing and tourism. Nevertheless, the degradation of coral reefs is an escalating global concern. Numerous factors, both natural and human-induced, contribute to the deterioration of this ecosystem. The intricate cause-and-effect interactions among the elements affecting coral reef degradation in the waters of Palopo City can be elucidated through the Causal Loop Diagram (CLD) methodology (Fig. 4). Causal loop diagrams serve as an efficient modeling instrument. CLD elucidates the dynamic interactions among variables that mutually influence one another, both positively and negatively [34], [35].

The causal loop graphic indicates that inadequate government coordination has led to heightened harm to coral reefs, evidenced by reduced live coral cover and ecological degradation. The inadequate empowerment of the community serves as a contributing cause to this state, underscoring the significance of local involvement in the management of coral reef ecosystems in the waters of Palopo City. Christie Research [36] indicates that conservation efforts for marine ecosystems, such as coral reefs, frequently falter due to local communities' lack of equitable involvement.

Environmentally detrimental fishing practices and the continued implementation of mass tourism in Palopo City adversely affect the coral reef ecosystem. These two variables directly exacerbate waste pollution and harm the marine environment, ultimately adversely affecting coral ecosystems. Overfishing and the utilization of damaging fishing equipment, such as bottom trawl nets or explosive devices, can lead to the destruction of coral reef ecosystems. Research by Kalyan De [37] elucidated that inadequately managed diving and snorkeling tourism frequently results in physical harm to coral from direct or inadvertent contact by tourists.

Development in the coastal regions of Palopo City frequently leads to an escalation of garbage entering the ocean. This garbage typically exists in solid or liquid form, impacting water quality and thereby hastening the deterioration of coral reefs. Research [38] indicates that waste contaminates aquatic environments and leads to bioaccumulation in marine creatures, impacting the food chain. The growing human demand for marine resources, for both economic pursuits and tourism, has stimulated the proliferation of cultivation practices, such as seaweed farming and floating net cages (KJA). Nevertheless, if not judiciously managed, these activities can intensify harm to coral reefs by elevating waste levels and diminishing water quality [39]. The rising population in Palopo City exerts strain on the ecology due to heightened demand for natural resources and land. According to BPS statistics from Palopo City for 2023 [40], the population of Palopo City is projected to reach 177,526 individuals. The population growth significantly influences the escalation of development activities in coastal regions, resulting in the degradation of coral habitats. This aligns with the findings of [41] and [42] that population growth exacerbates the deterioration of seawater quality, hastens coral bleaching, and diminishes the resilience of coral reefs to environmental disturbances, alongside heightened developmental activities in coastal regions, including land reclamation, infrastructure expansion, and unsustainable tourism practices. Coral reefs in the waters of Palopo City are adversely impacted by natural forces, including bleaching and climate change, which directly influence their health. While humans cannot entirely regulate these causes, techniques for mitigation and adaptation can be implemented to diminish their effects.

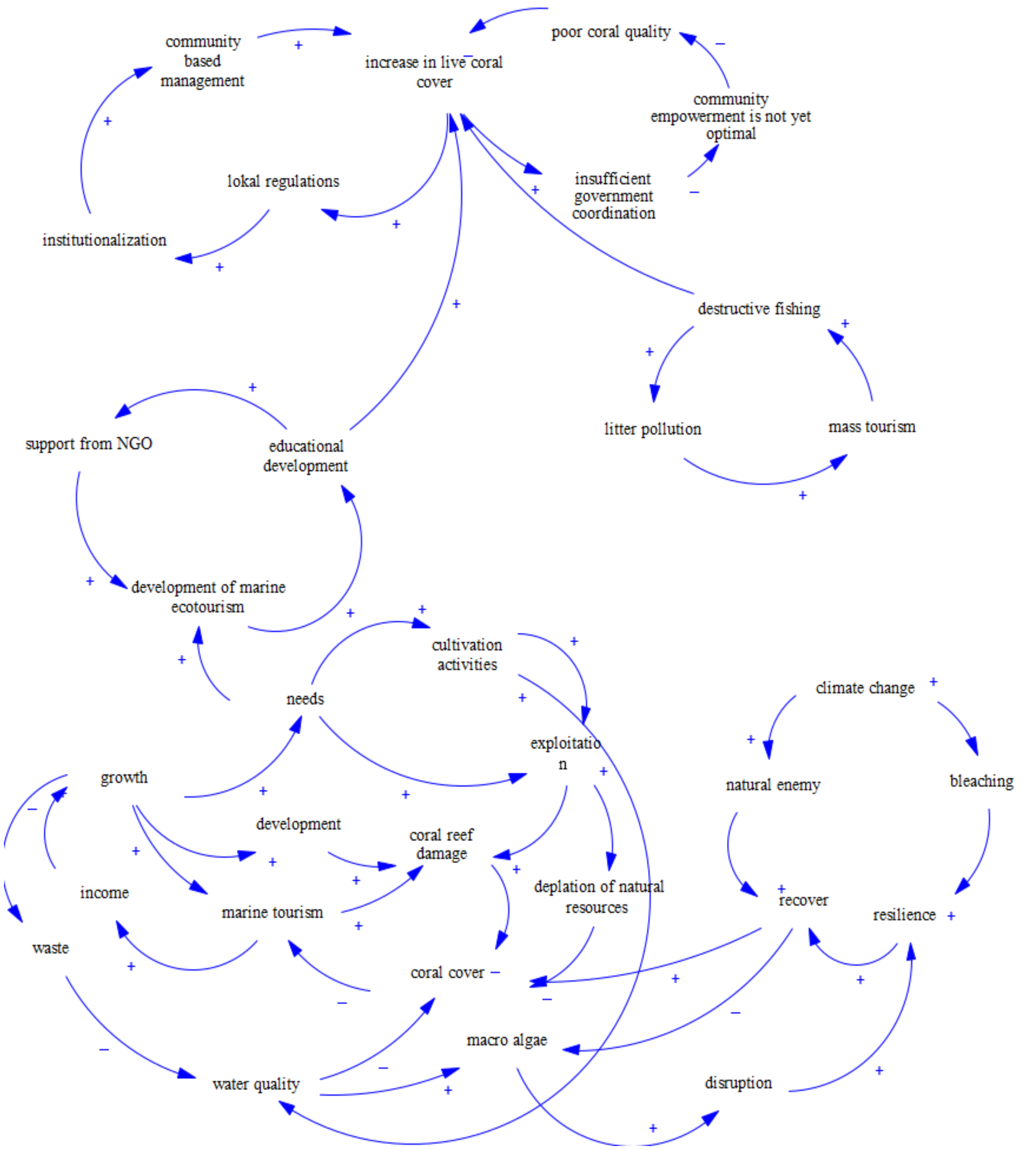


Fig. 4. Causal Loop Diagram

Policy Framework for Coral Reef Ecosystem Advancement in the Waters of Palopo City

Formulating coral reef ecosystem management strategies is a strategic measure to conserve and rehabilitate delicate marine ecosystems while offering ecological, economic, social, and institutional advantages. This policy scenario must adopt a comprehensive approach grounded in sustainability principles, considering conservation requirements and the empowerment of local communities [43], [44]. The management of coral reef ecosystems must encompass identifying and mapping damaged and fragile coral reef areas. This entails assessing the state of coral reefs and current conditions, including the extent of damage inflicted by climate change, pollution, harmful fishing practices, population increase, and mass tourism. Dynamic alterations in coral reef coverage were simulated based on mapping data, and management strategies were formulated based on insights obtained from comprehensive interviews with each major stakeholder. The prioritized strategies for managing coral reef ecosystems in Palopo City's waters are: 1) Water resource management utilizing Integrated Coastal Zone Management; 2) Establishing local regulations for sustainable marine tourism; and 3) Forming conservation groups within ecotourism initiatives. Dynamic modelling encompasses these three methodologies along with all factors that affect live coral cover, both positively and negatively. Figure 5 illustrates the Stock Flow Diagram created with Vensim.

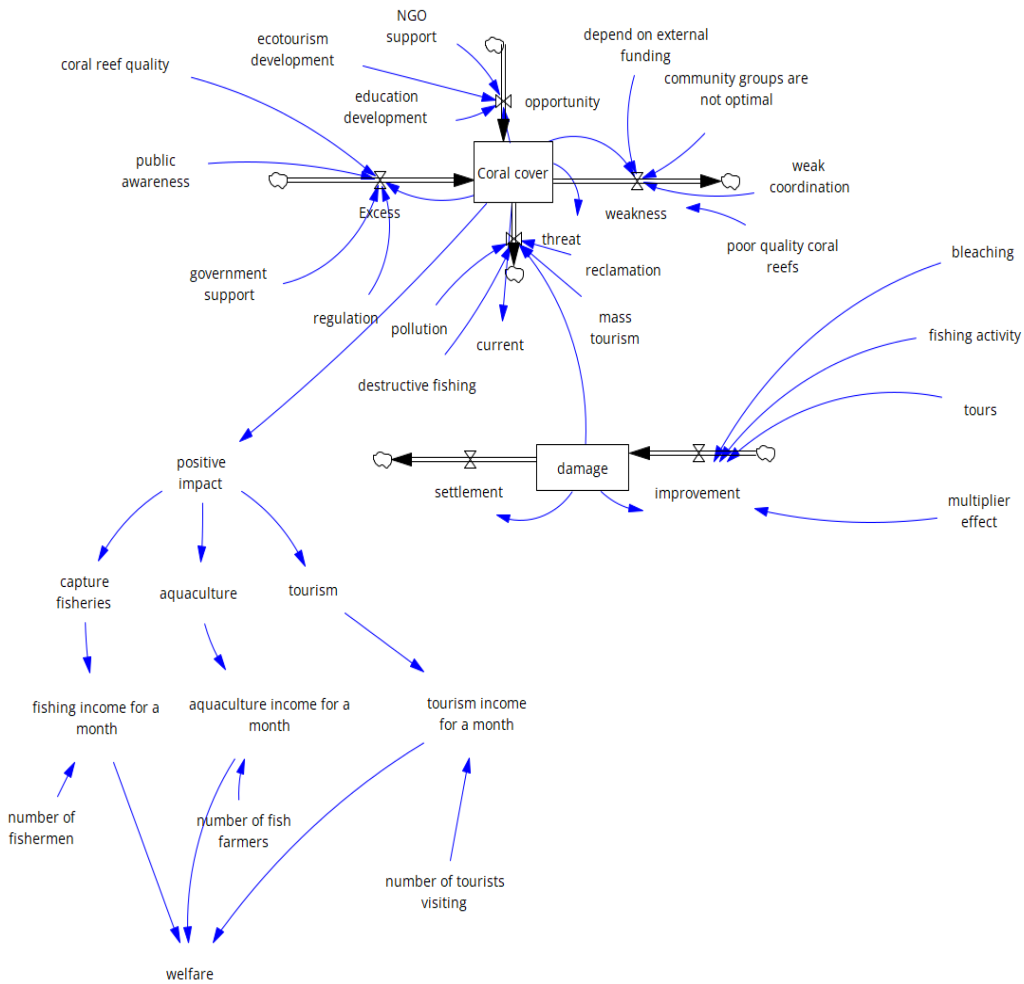


Fig. 5. Stock and Flow Diagram

Figure 6 illustrates the simulated outcomes of coral reef ecosystem management, comparing the implementation of all selected techniques with the absence of coral reef management. This presents the execution of strategy 1, specifically integrated coastal zone management (ICZM)-based water resource management, which has the potential to enhance coral reef cover by as much as 35% from the present state, where the average coral reef cover in the waters of Palopo City, according to final calculations, is 15%. This aligns with the challenges encountered in water resource management, where the management concept remains sectoral, and Integrated Coastal Zone Management (ICZM) has yet to be adopted.

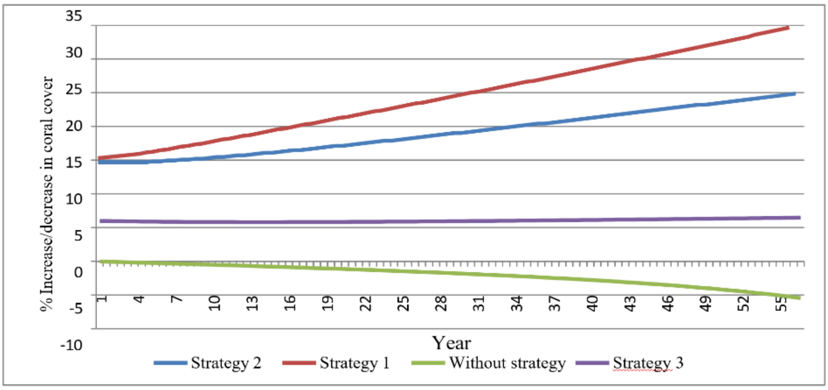


Fig. 6. Results of dynamic modeling simulations of live coral cover in Palopo City

Water resource management informed by Integrated Coastal Zone Management (ICZM) can yield enduring advantages for coral reef ecosystems, hence facilitating the survival of diverse marine species and enhancing the well-being of coastal communities [45], [46], [47]. Additionally, policies for managing tourism in coastal and marine areas are not yet optimal. The tourist model utilized in Palopo City continues to adhere to a mass tourism framework, lacking the implementation of ecotourism principles and failing to engage the local people. Well-managed ecotourism zones can expedite the restoration of deteriorated coral reef ecosystems by regulating harmful activities [48]. Conversely, ecotourism offers substantial advantages in empowering local populations. By actively participating in ecotourism management, local communities can secure a sustainable income while preserving the environment [49], [50]. If this issue can be addressed, coral reefs will thrive in the long term, resulting in an increase in live coral coverage. The modeling results indicate that this growth transpired after a century. Concurrently, the second most effective option is establishing a localized regulatory framework for sustainable marine tourism operations, aiming for a 20% increase in live coral cover from the current state within the next century. The enforcement of municipal legislation about maritime tourism activities may encompass various elements, including the limitation of tourist numbers, the designation of conservation zones, and the specification of permissible activities [51], [52], [53]. The subsequent phase involves the establishment of coastal and marine conservation organizations. This method has the potential to augment coral reef coverage in the waters of Palopo City by over 15% over a century. This is acceptable as coastal and marine conservation organizations employ an integrated approach, encompassing education for local communities, monitoring of aquatic ecosystems, and implementing conservation practices informed by contemporary and traditional scientific knowledge. The education and engagement of local communities are crucial, as they play a direct role in preserving the coral reef environment.

Moreover, conservation organizations can engage in direct initiatives such as coral restoration, specifically replanting damaged coral reefs and safeguarding marine habitats from overexploitation. Such activities seek to enhance live coral coverage and establish protective zones that can expedite the healing process of coral ecosystems. Numerous conservation organizations have already been established in Palopo City, including the Lawarani Conservation Group, the Tourism Awareness Group, the Palopo City Wallacea Association, and the Ponjalae Fishermen's Group. The comprehensive function of conservation organizations in Palopo City is delineated in Table 6.

Table 6. The Role of Conservation Groups in Coral Reef Management

No	Conservation Group	Role
1	Lawarani Conservation Group	➢ Carry out rehabilitation, maintain coral reefs ➢ Building cooperation with relevant stakeholders
2	Tourism Awareness Group	➢ Maintain, monitor and control coral reef ecosystems for tourists and from other activities that could damage them ➢ Providing coral reef transplantation training to fishing communities
3	Palopo City Wallacea Association	➢ Carry out regional mapping and determine zoning based on the regional potential of each sub-district ➢ Manage the potential of human resources and natural resources with transparency and accountability
4	Ponjalae Fishermen Group	➢ Monitoring and maintaining coral reef ecosystems ➢ Providing coral reef transplant media

Policies and laws safeguarding against actions detrimental to corals and incentives for preserving coastal ecosystems will foster an environment conducive to coral growth. Conversely, without implementing a strategy, living coral cover is projected to diminish by merely 5% from its current state over the next century. This data indicates that live coral cover varies within a similar range, exhibiting no significant reduction. A simulation process will be conducted for each approach individually to facilitate comparing the simulation outcomes for each strategy.

Conclusions

The coral reef ecosystem in the waters of Palopo City is in a damaged condition with only 0-15% live coral cover. The destruction of coral reefs is caused by destructive fishing practices using bombs and potassium, sedimentation, mass tourism, and pollution. This is evidenced by the high cover of dead corals (65-84%) at all points of the research site. Based on the results of dynamic modeling (Causal Loop Diagram and Stock and Flow), it shows that there are three priority policy scenarios that are most effective to restore coral reef ecosystems in Palopo City, such as the implementation of integrated coastal management (ICM) based on aquatic resource management. This strategy is projected to increase live coral cover by up to 35% within the next 100 years. Other supporting strategies, such as the creation of local rules for sustainable marine tourism and the establishment of coastal and marine conservation groups, also have a positive impact, although not as large as the integrated coastal management strategy. The cover of live corals in the waters of Palopo City is predicted to continue to decline by 5% from current conditions in the next 100 years if no policy intervention is carried out. Thus, the implementation of a holistic and integrated coastal management model that involves all stakeholders and is supported by local regulations and the active participation of conservation groups is the main key in realizing sustainable coral reef ecosystem management in Palopo City.

Acknowledgements

We are deeply appreciative of the Ministry of Education, Culture, Research, and Technology (Kemdikbud Ristek Dikti) of the Republic of Indonesia and other relevant parties for their assistance in the execution of this research through the 2024 Regular Fundamental Research funding program. This support is extremely valuable in enhancing the quality of research and promoting the advancement of science in the areas in which we specialize.

References

[1] C. J. Harsindhi, D. G. Bengen, N. P. Zamani, and F. Kurniawan, "Abundance and spatial distribution of reef fish based on coral lifeforms at Tidung Island, Seribu Islands, Jakarta Bay," *AACL Bioflux*, vol. 13, no. 2, pp. 736–745, 2020, [Online]. Available: http://www.bioflux.com.ro/aacl

[2] A. A. Saputra and A. Faisal Bakti, "Communication Strategy in Coral Reef Conservation Program by the NGO KPPLB to the Belitung Community," *International Journal of Environmental Communication*, vol. 1, no. 2, pp. 103–115, Dec. 2023.

[3] M. Gudka *et al.*, "Complex coral reefs offer hope for management in a Marine Protected Area in Zanzibar," *Reg. Stud. Mar. Sci.*, vol. 77, pp. 1–12, Dec. 2024, doi: 10.1016/j.rsma.2024.103667.

[4] Irwan, Y. Arafat, Awaluddin, and Supryady, "Kondisi Terumbu Karang Dan Ikan Karang Teluk Bone Di Kabupaten Bone," *Jurnal Salamata*, vol. 1, no. 2, pp. 7–14, 2018.

[5] Y. Sulistyadi, F. Eddyono, and B. Hasibuan, "Model of Sustainable Tourism Development Strategy of the Thousand Islands Tourism Area – Jakarta," *Journal of Economics, Management and Trade*, vol. 19, no. 1, pp. 1–17, 2017, doi: 10.9734/jemt/2017/35989.

[6] Y. Sulistyadi, R. H. Demolingo, B. S. Latif, T. Indrajaya, P. P. Adnyana, and K. Wiweka, "The Implementation of Integrated Coastal Management in the Development of Sustainability-Based Geotourism: A Case Study of Olele, Indonesia," *Sustainability (Switzerland)*, vol. 16, no. 3, pp. 1–25, Feb. 2024, doi: 10.3390/su16031272.

[7] S. English, C. Wilkinson, and V. Baker, *Survey Manual for Tropical Marine Resoucers 2nd Edition*. Australia: Australian Institut of Marine Science, 1997.

[8] K. Soong, "Colony size as a species character in massive reef corals," *Coral Reefs*, vol. 12, no. 2, pp. 77–83, Jul. 1993, doi: 10.1007/BF00302106.

[9] L. Gastoldi and S. Cinti, "(Bio)sensors applied to coral reefs' health monitoring: a critical overview," *Green Analytical Chemistry*, vol. 4, Mar. 2023, doi: 10.1016/j.greeac.2023.100049.

[10] N. Najmi, E. Lisdayanti, F. Lubis, and A. S. Darmarini, "The conditions of coral reef ecosystem on Seureudong Island, South Aceh, Indonesia," *Jurnal Pengelolaan Sumberdaya Alam dan Lingkungan*, vol. 13, no. 4, pp. 624–633, 2023, doi: 10.29244/jpsl.13.4.624-633.

[11] Y. P. Paulangan, A. Fahrudin, D. Sutrisno, and D. G. Bengen, "Distribution and condition of coral reef ecosystem in Tanah Merah Bay, Jayapura, Papua, Indonesia," *AACL Bioflux*, vol. 12, no. 2, pp. 502–512, 2019, [Online]. Available: http://www.bioflux.com.ro/aacl

[12] D. Kolibongso, H. G. Alfani, F. A. Loinenak, L. Sembel, and G. Y. S. Purba, "Pengaruh Sedimentasi terhadap Tutupan Terumbu Karang di Perairan Arfai, Manokwari Indonesia," *Jurnal Kelautan Tropis*, vol. 27, no. 2, pp. 225–235, Jun. 2024, doi: 10.14710/jkt.v27i2.22130.

[13] Y. P. Paulangan *et al.*, "Socio-economic and institutional sustainability management of coral reef ecosystem based on local communities in Teluk Tanah Merah (Depapre), Jayapura, Indonesia," in *IOP Conference Series: Earth and Environmental Science*, Institute of Physics Publishing, Mar. 2019. doi: 10.1088/1755-1315/241/1/012034.

[14] D. W. Dela Cruz and P. L. Harrison, "Reef location and season, but not recruitment substrate contour and composition, affect coral recruitment patterns," *J. Exp. Mar. Biol. Ecol.*, vol. 578, no. 152029, Sep. 2024, doi: 10.1016/j.jembe.2024.152029.

[15] S. A. Bitterwolf, B. G. Reguero, C. D. Storlazzi, and M. W. Beck, "Shifting sands: The influence of coral reefs on shoreline erosion from short-term storm protection to long-term disequilibrium," *Nature-Based Solutions*, vol. 6, p. 100174, Dec. 2024, doi: 10.1016/j.nbsj.2024.100174.

[16] C. S. Rogers and C. E. Ramos-Scharrón, "Assessing Effects of Sediment Delivery to Coral Reefs: A Caribbean Watershed Perspective," Jan. 28, 2022, *Frontiers Media S.A.* doi: 10.3389/fmars.2021.773968.

[17] M. F. M. Hanapiah, S. Saad, Z. Ahmad, M. H. Yusof, and M. F. A. Khodzori, "Assessment of benthic and coral community structure in an inshore reef in Balok, Pahang, Malaysia," *Biodiversitas*, vol. 20, no. 3, pp. 872–877, Mar. 2019, doi: 10.13057/biodiv/d200335.

[18] E. G. Knoester, N. Klerks, S. B. Vroege-Kolkman, A. J. Murk, S. O. Sande, and R. Osinga, "Coral Predation and Implications for Restoration of Kenyan Reefs: The Effects of Site Selection, Coral Species and Fisheries Management," *J. Exp. Mar. Biol. Ecol.*, vol. 566, p. 151924, Sep. 2023, doi: 10.1016/j.jembe.2023.151924.

[19] P. D. Samuel, M. Fakhri, C. S. U. Dewi, J. Ellona, and M. C. Anam, "Percentage of Hard Coral Cover and Coral Recruitment on in Bangsring Beach, Banyuwangi Regency," *Research Journal of Life Science*, vol. 10, no. 1, pp. 21–28, Apr. 2023, doi: 10.21776/ub.rjls.2023.010.01.3.

[20] Mahmudin, C. Rani, and Hamzah, "Condition of Coral and Reef Fish in The Location of Fish Catching Using Dynamite Fishing in Kapoposang Water Park and The Surrounding Sea," *Jurnal Ilmu Kelautan*, vol. 6, no. 1, pp. 1–6, 2020.

[21] N. Najmi, M. Suriani, M. M. Rahmi, and A. S. Darmarini, "Diversity of marine plankton in coral reef ecosystems at Gosong Island, Southwest Aceh," in *E3S Web of Conferences*, EDP Sciences, Jan. 2022. doi: 10.1051/e3sconf/202233903004.

[22] D. Sahetapy, S. Widayati, and M. Sangadji, "Community Activity Impact on Coral Reefs Ecosystem in The Coastal Waters Katapang Orchard West Seram District," *Jurnal TRITON*, vol. 13, no. 2, pp. 105–114, 2017.

[23] D. J. Suggett, M. Edwards, D. Cotton, M. Hein, and E. F. Camp, "An integrative framework for sustainable coral reef restoration," *One Earth*, vol. 6, no. 6, pp. 666–681, 2023, doi: 10.1016/j.oneear.2023.05.007.

[24] S. B. Tebbett, R. A. Morais, C. H. R. Goatley, and D. R. Bellwood, “Collapsing ecosystem functions on an inshore coral reef,” *J. Environ. Manage.*, vol. 289, Jul. 2021, doi: 10.1016/j.jenvman.2021.112471.
[25] M. C. Ladd and A. A. Shantz, “Trophic Interactions in Coral Reef Restoration: A review,” *Food Webs*, vol. 24, Sep. 2020, doi: 10.1016/j.fooweb.2020.e00149.
[26] Y. Nozawa *et al.*, “Latitudinal variation in growth and survival of juvenile corals in the West and South Pacific,” *Coral Reefs*, vol. 40, no. 5, pp. 1463–1471, Oct. 2021, doi: 10.1007/s00338-021-02169-9.
[27] R. H. Richmond, Y. Golbuu, and A. J. Shelton, *Successful Management of Coral Reef-Watershed Networks*. Elsevier Inc., 2019. doi: 10.1016/B978-0-12-814003-1.00026-5.
[28] J. Figueroa-Pico, A. J. Carpio, and F. S. Tortosa, “Turbidity: A key factor in the estimation of fish species richness and abundance in the rocky reefs of Ecuador,” *Ecol. Indic.*, vol. 111, no. December 2019, p. 106021, 2020, doi: 10.1016/j.ecolind.2019.106021.
[29] Keputusan Menteri Negara Lingkungan Hidup Nomor 51, *Keputusan MENLH Nomor 51 Tahun 2004 tentang Baku Mutu Air Laut*. 2004.
[30] F. Yulianda *et al.*, *Kebijakan Konservasi Perairan Laut dan Nilai Valuasi Ekonomi*. Bogor: IPB Press, 2010.
[31] Et. al Estradivari, Handayani, “Kawasan Konservasi Perairan,” *WWF Jakarta Indonesia*, 2017, [Online]. Available: http://awsassets.wwf.or.id/downloads/mpa_for_fisheries_wwf_indonesia_2017.pdf
[32] J. E. N. (John E. N. Veron and Mary. Stafford-Smith, *Corals of the world*. Australian Institute of Marine Science, 2000.
[33] T. E. Y. Sari, S. H. Wisudo, D. R. Monintja, and T. Purwaka, “Konflik Perikanan Tangkap Di Perairan Kabupaten Bengkalis Provinsi Riau,” *Marine Fisheries : Journal of Marine Fisheries Technology and Management*, vol. 1, no. 2, p. 11, 2012, doi: 10.29244/jmf.1.2.11-20.
[34] H. A. Mubarok, S. H. Wisudo, and B. H. Iskandar, “CCRF Perspective on Spearfisheries in Karimunjawa Islands, Jepara District Central Java,” *Marine Fisheries : Journal of Marine Fisheries Technology and Management*, vol. 3, no. 2, p. 155, 2016, doi: 10.29244/jmf.3.2.155-122.
[35] A. Tomoaia-Cotisel, H. Kim, S. Allen, and K. Blanchet, “Causal Loop Diagrams A tool for visualizing the system structure resulting in emergent system behaviour,” in *EBOOK: Applied Systems Thinking for Health Systems Research: A Methodological Handbook*, McGraw-Hill Education, 2017, pp. 97–114. [Online]. Available: http://public.wsu.edu/~forda/Ch%201.pdf
[36] B. Zekan, C. Weismayer, U. Gunter, B. Schuh, and S. Sedlacek, “Regional sustainability and tourism carrying capacities,” *J. Clean. Prod.*, vol. 339, no. January, p. 130624, 2022, doi: 10.1016/j.jclepro.2022.130624.
[37] K. M. Hamelin, A. T. Charles, and M. Bailey, “Community knowledge as a cornerstone for fisheries management,” *Ecology and Society*, vol. 29, no. 1, Mar. 2024, doi: 10.5751/ES-14552-290126.
[38] E. M. Tuuri and S. C. Leterme, “How plastic debris and associated chemicals impact the marine food web: A review,” *Environmental Pollution*, vol. 321, Mar. 2023, doi: 10.1016/j.envpol.2023.121156.

[39] S. Mulyani, A. Tuwo, R. Syamsuddin, and J. Jompa, "Effect of seaweed Kappaphycus alvarezii aquaculture on growth and survival of coral Acropora muricata," *AACL Bioflux*, vol. 11, no. 6, pp. 1792–1798, 2018, [Online]. Available: http://www.bioflux.com.ro/aacl

[40] BPS, *Statistik Indonesia*. Badan Pusat Statistik, 2023.

[41] E. C. Heery *et al.*, "Urban coral reefs: Degradation and resilience of hard coral assemblages in coastal cities of East and Southeast Asia," *Mar. Pollut. Bull.*, vol. 135, pp. 654–681, Oct. 2018, doi: 10.1016/j.marpolbul.2018.07.041.

[42] L. Burke and M. Spalding, "Shoreline protection by the world's coral reefs: Mapping the benefits to people, assets, and infrastructure," *Mar. Policy*, vol. 146, no. September, p. 105311, 2022, doi: 10.1016/j.marpol.2022.105311.

[43] H. Kurniawan, R. Setiawan, S. Vladimirov Mladenov, and M. Ardiansyah, "Sustainable Development Through Community Empowerment Based On Local Wisdom," *International Journal of Progressive Sciences and Technologies (IJPSAT*, vol. 41, no. 2, pp. 164–176, Nov. 2023, [Online]. Available: https://idm.kemendesa.go.id/

[44] N. P. Hariram, K. B. Mekha, V. Suganthan, and K. Sudhakar, "Sustainalism: An Integrated Socio-Economic-Environmental Model to Address Sustainable Development and Sustainability," *Sustainability (Switzerland)*, vol. 15, no. 13, pp. 2–37, Jul. 2023, doi: 10.3390/su151310682.

[45] D. P. Safitri, A. Hakim, M. R. K. Muluk, and F. Putra, "Sustainable coastal management in supporting blue economy: An Indonesian experience," in *IOP Conference Series: Earth and Environmental Science*, Institute of Physics, 2023, pp. 1–8. doi: 10.1088/1755-1315/1148/1/012039.

[46] M. A. R. Khan, "Sustainable Coastal Zone Management: Need for a Holistic Approach for Bangladesh," *Journal of Management and Sustainability*, vol. 10, no. 2, p. 112, Nov. 2020, doi: 10.5539/jms.v10n2p112.

[47] I. Setiawan, B. Rianto, and Sudirman, "Implementation of Coastal Area Management Policy Based on Sustainable Development In Banyuwangi Regency," *International Journal of Applied Research in Social Sciences*, vol. 4, no. 2, pp. 35–50, Mar. 2022, doi: 10.51594/ijarss.v4i2.311.

[48] B. Kristianto, Novindra, and K. Sapanli, "Ecotourism: An alternative solution for socio-ecological crisis in Pahawang Island, Indonesia," in *IOP Conference Series: Earth and Environmental Science*, Institute of Physics, 2024, pp. 1–6. doi: 10.1088/1755-1315/1359/1/012052.

[49] F. Pineda, J. Padilla, J. C. Granobles-Torres, A. Echeverri-Rubio, C. M. Botero, and A. Suarez, "Community preferences for participating in ecotourism: A case study in a coastal lagoon in Colombia," *Environmental Challenges*, vol. 11, Apr. 2023, doi: 10.1016/j.envc.2023.100713.

[50] N. D. Tien *et al.*, "Community-based ecotourism for sustainability: An evaluative analysis of Binh Son district, Quang Ngai province in Vietnam," *Social Sciences and Humanities Open*, vol. 9, pp. 1–17, Jan. 2024, doi: 10.1016/j.ssaho.2024.100807.

[51] A. Mahmud and A. S. Rilus A. Kinseng, "Zonasi Konservasu untuk Siapa ? Pengaturan Perairan Laut Taman Nasional Bali Barat," *Jurnal Ilmu Sosial dan Ilmu Politik (JSP)*, vol. 18, no. 3, pp. 237–251, Mar. 2015.

[52] M. T. A. Shampa, N. J. Shimu, K. M. A. Chowdhury, M. M. Islam, and M. K. Ahmed, "A comprehensive review on sustainable coastal zone management in Bangladesh: Present

status and the way forward," *Heliyon*, vol. 9, no. 8, pp. 1–18, Aug. 2023, doi: 10.1016/j.heliyon.2023.e18190.

[53] C. M. Batista, C. I. Pereira, and C. M. Botero, "Improving a decree law about coastal zone management in a small island developing state: The case of Cuba," *Mar. Policy*, vol. 101, no. March 2018, pp. 93–107, 2019, doi: 10.1016/j.marpol.2018.12.030.

Received: June 22, 2025
Accepted: February 10, 2026