Sustainable coral reef ecosystem management model (Case study of Palopo City, South Sulawesi Province)

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Abstract. Palopo City, located in South Sulawesi Province, is a popular tourist destination due to its abundant coastal and marine resources, making it an ideal location for sustainable coral reef ecosystem management. The coastal and marine biological resources of ecological significance encompass coral reef ecosystems, coral fish, and fisheries. In addition to their biological significance, coral reef ecosystems also possess considerable aesthetic value for the advancement of marine tourism. The objective of this study was to assess the state of coral reefs in the seas of Palopo City, ascertain the appropriate suitability category of marine ecotourism for the various snorkeling and diving activities that can be employed in the waters of Palopo City, and formulate a proficient strategy for managing the coral reef ecosystem to facilitate the growth of marine ecotourism in the City of Palopo. Data on biophysical parameters was gathered by field surveys and augmented with secondary data. The analytical methodology comprises two components: tourism suitability analysis and process hierarchy analysis (AHP). Based on the proportion of live coral cover ranging from 0 to 24.9%, the research findings indicate that the coral reefs in the waters of Palopo City are classified as damaged/poor. Marine coral reefs suffer from degradation caused by fishing operations employing non-sustainable gear. Based on limiting variables such as live coral cover, varieties of coral fish, and the number of lifeforms, the appropriateness class for marine tourism in Palopo City waters for the snorkeling and diving category is classified as unsuitable (N). The primary approach in the management of coral reef ecosystems in Palopo City is to establish the zoning of coastal and marine habitats to safeguard coral reef ecosystems and promote sustainable ecotourism.

Key Words: coral fish, coral reefs, marine ecotourism, recreational appropriateness, seas of Palopo City.

Introduction. Coral reefs contain invaluable natural resources for the Indonesian population. According to Dahuri (2001), the estimated area of coral reefs in Indonesian waters exceeds 60000 km^2 and is distributed extensively from the western to the eastern provinces of the country. The territorial seas of Indonesia harbor approximately one-eighth of the global coral reefs and exhibit a higher level of aquatic biota diversity in comparison to other countries in Southeast Asia. Coral reef ecosystems play a crucial dual role in coastal regions, serving both ecological and economic interests. Ecologically, the coral reef ecosystem serves as a habitat for a diverse range of creatures that rely on it for protection, sustenance, and reproduction (Eddy et al 2021; Tebbett et al 2021). Furthermore, the presence of coral reef ecosystems can provide protection to beaches from the damaging effects of waves and abrasion (Elise et al 2019). From an economic perspective, the vibrant coral reef ecosystem serves as a destination for marine tourism (French et al 2017; Cusack et al 2021), and offers significant fishing opportunities, particularly for traditional fishermen (Yusuf et al 2018; Araujo et al 2023). Palopo City is situated in South Sulawesi Province, where the majority of its seas are characterized by a coral reef ecosystem, specifically the fringing reef type. The abundant capacity of the coral reef ecosystem has led to the utilization of the coast of Palopo City as a marine tourism destination and fishing spot by the local coastal residents. Nevertheless, coral reef ecosystems are also undergoing deterioration due to human activities including the use of ecologically harmful fishing equipment, tourism activities, and coastal development. Damage resulting from human activities will have a more severe and enduring effect (Ginting 2023). The degree of degradation directly correlates with the extent to which coral reefs lose their inherent biological and ecological traits (Pratchett et al 2014; Burke & Spalding 2022). Although some rehabilitation initiatives have been implemented, they have not yielded substantial outcomes. Hence, in order to maintain the long-term viability of the coral reef ecosystem in the waters of Palopo City, it is imperative to develop a management model that can ensure the sustainability of the coral reef ecosystem in the region. This model should encompass various management strategies and scenarios that consider ecological, social, economic, technological, and institutional factors (Bawole et al 2013; Paulangan et al 2019a). Undertaking this research is crucial because the intricate nature of the coral reef issue directly affects the decrease in fish populations, which serves as the primary source of income for fishermen. Consequently, this can lead to the cessation of marine tourism in the coastal and marine regions of Palopo City, so causing disruption to the social and economic stability of the city. Presently, the management of coral reefs in the waters of Palopo City is fragmented, without strategic planning and integration with other initiatives implemented by relevant stakeholders in Palopo City. This management approach has failed to take into account certain factors that can impact the long-term viability of coral reef ecosystems. Hence, in order to guarantee the long-term viability of the coral reef ecosystem in the seas of Palopo City, it is imperative to conduct a comprehensive analysis of the process hierarchy, considering ecological, social, economic, technological, and institutional factors. The aim of this study was to ascertain the factors and concerns of stakeholders involved in the management of coral reef ecosystems and develop policy models that prioritize the sustainable management of coral reef ecosystems to accommodate the marine tourist industry.

Material and Method

Description of the study sites. The study was conducted in Palopo City from July to September 2023. The research site was selected based on the observation that Palopo City is situated in a coastal region that is very susceptible to conflicts that have the potential to harm the coral reefs in the vicinity. Moreover, it possesses considerable potential, thereby enabling it to effectively cater to the requirements of the neighboring population. The map of the research location can be seen in Figure 1.

Figure 1. Research location at Palopo, South of Sulawesi, Indonesia.

Underwater photo transect (UPT). The transect photo approach is an advancement and refinement of the LIT and PIT techniques. The quadrat transect designated for coral observation measured 1×1 m^2 and was positioned parallel to the transect line up to a distance of 50 m, at the location of the transect line points that have been installed before. The quadrat transects were laid according to a zig-zag pattern. Every individual coral organism that was encountered was captured in photographs and subsequently classified based on its state and taxonomic division. Analysis of data provided information on the proportion of coral cover, the prevalence of different life forms, the total number of life forms, and the classification of dead coral and live coral. Transect photographs were captured with an underwater camera. Images were captured at regular intervals of 1 m along a transect line measuring 50 m in length, at a depth ranging from 3 to 15 m, at the site of the previously established permanent transect point (Labrosse et al 2002; Adji et al 2017; Brook et al 2017).

Underwater visual census (UVC). The UVC technique employs the identical line transect as found in the coral community observation transect as described by Brook et al (2017) and Pais & Cabral (2018). For the practical implementation of this approach in the field, a diver visually detects coral fish swimming above a 25-m long line transect and documents all fish species located 2.5 m to the left and right of the line transect (Soldo & Glavičić 2020).

Semi directive interview. Interviews were conducted in a semi-directed manner where the informant was guided in discussions by the researcher regarding the research objectives. Informants included several key stakeholders related to the use and management of coral reef ecosystems in the waters of Palopo City. The number of informants was 30 people. Determining the source of key informants/stakeholders was carried out using the purposive sampling method. Purposive sampling is a sampling method based on certain or deliberate considerations (Tongco 2007; Lenaini 2021). Key stakeholders in this research are the Mayor of Palopo, Palopo City Maritime Affairs and Fisheries Service, Palopo City Environmental Service, Palopo City Regional People's Representative Council, Palopo City Regional Planning and Development Agency, Regional Research and Development Agency, District Government, Subdistrict Government, traditional stakeholders, and community groups.

Coral cover percentage. Estimation of coral reef coverage using the Coral Point with Excel (CPCE) software involved conducting picture analysis by randomly selecting point samples for each frame, which were then calculated using a specific algorithm (Kohler & Gill 2006).

$$\%\,Appearance = \frac{number\ of\ category\ points}{number\ of\ random\ points}\ X\ 100$$

In accordance with Decree of the Minister of State for Environment No. 4 of 2001 Regarding: Standard Criteria for Coral Reef Damage (2001), coral reef condition classifications are determined by the proportion of live coral cover. These categories are as follows: 0–24.9% (damaged/poor), 25–49.9% (medium), 50–74.9% (good), and 75–100% (very good).

Reef fish abundance index. Reef fish abundance refers to the population of coral fish present at a specific observation site, measured as the number of fish per unit area of the observation transect. The abundance index was determined by using the following formula (Labrosse et al 2002; Prasetya & Santoso 2022).

$$K = \frac{in}{A}$$

Where: K - abundance of reef fish (ind m^{-2}); in - number of coral fish at the 1st observation station (ind); A - observation transect area (m^2).

Reef fish diversity index (H'). The diversity index (H') was calculated using the Shannon-Wiener formula (Odum 1959), as follows:

$$H' = \sum_{i=1}^{n} Pi \ ln \ Pi$$

$$Pi = in/N$$

Where: H' - diversity index; Pi - probability of species i from total individuals; S - number of species; in - number of individuals of the 1st species; N - total number of individuals of the species; H'≤2 - low diversity; 2<H'≤3 - medium diversity; H'>3 - high diversity.

Reef fish uniformity index (e). To calculate species uniformity, the uniformity index formula was used (Odum 1959):

$$E = \frac{H'}{ln \ ln \ S}$$

Where: *E* - uniformity index; *H'* - diversity index; *S* - number of species.

Dynamic model analysis. Causal loop diagram analysis emphasizes a deep and holistic understanding of the complexity of the interaction of factors that affect the sustainability of coral reef ecosystem management in Palopo City. Causal loop diagram analysis explains the interrelated causal network covering ecological, social, economic, technological and institutional aspects that then form a complex system dynamic. Causal loop diagrams are a highly powerful modelling tool. The concept of causal loop diagrams elucidates the dynamic interplay among variables that exert mutual influence, encompassing both positive and negative effects (Tomoaia-Cotisel et al 2017).

Process hierarchy analysis. Analytic Hierarchy Process (AHP) analysis was employed to derive priority policy models for the management of coral reef ecosystems. These models are integrated with local wisdom systems and consider ecological, economic, social, technological, and institutional factors (Figure 2).

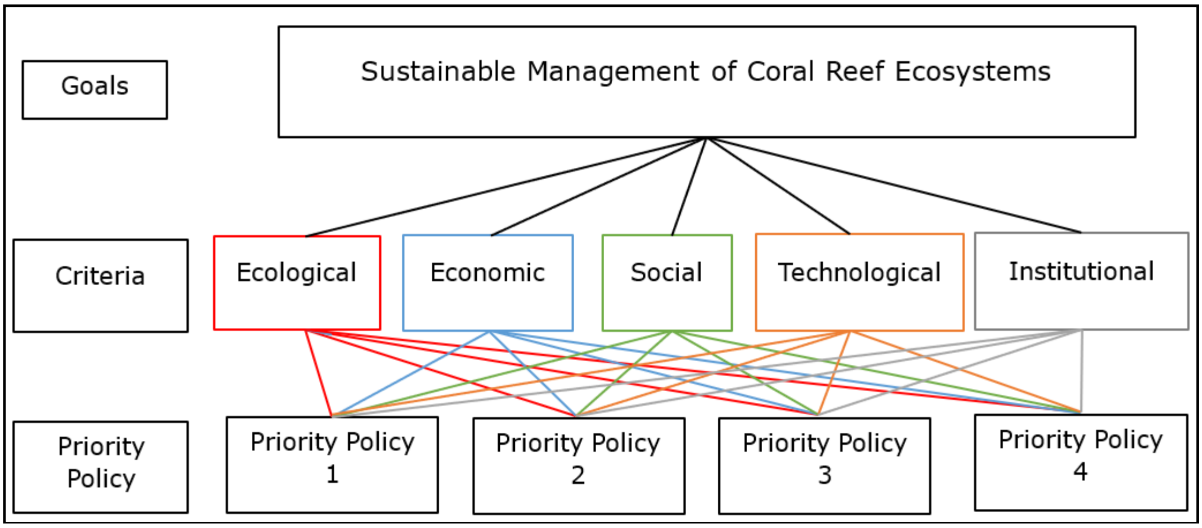

Figure 2. Hierarchy of priority policies for coral reef ecosystem management in Palopo City waters.

Results and Discussion

Condition of coral reefs in Palopo City waters. There are 8 distinct varieties of coral present in the observation stations in the seas of Palopo City. Digitate *Acropora* (ACD) consists of 94 colonies. The distribution of these colonies is as follows: station 1 has 10 colonies at a depth of 3 m, while station 2 supports 19 colonies at the same depth. Station 2 contains 2 colonies at a depth of 3 m and 8 colonies at a depth of 10 m. Station 3 comprises 33 colonies at a depth of 3 m and 22 colonies at a depth of 10 m. A total of 114 foliose coral (CF) colonies were seen, distributed as follows: 15 colonies were found at station 1 at a depth of 3 m, and 32 colonies at a depth of 10 m. Station 2 did not exhibit any living forms, but station 3 had 14 colonies at a depth of 3 m, and 53 colonies at a depth of 10 m. A total of 30 colonies of mushroom corals (CMR) were seen, distributed as follows: 2 colonies at station 1 at a depth of 3 m, and 1 colony at a depth of 10 m. Station 2 did not exhibit any coral growth at depths of 3 and 10 m. Conversely, station 3 had 1 colony at a depth of 3 m and 26 colonies at a depth of 10 m. Branching *Acropora* (ACB) had 162 colonies, distributed as follows: 27 colonies were located at station 1 at a depth of 3 m, and 18 at 10 m. Station 2 hosted two colonies at 3 m. However, at a depth of 10 m, no colonies were detected. Station 3 comprised 44 colonies at a depth of 3 m and 71 at 10 m. 40 colonies of millepora coral (CME) were discovered, distributed as follows: 3 colonies at station 1 at 3 m, and 12 colonies at 10 m. Station 2 did not exhibit any coral growth at a depth of 3 m, but at a depth of 10 m, a single colony was observed. Station 3 contained 16 colonies at a depth of 3 m and 8 colonies at a depth of 10 m. The encrusting corals (CE) involved 125 colonies distributed as follows: 15 colonies were found at station 1 at a depth of 3 m, while 7 colonies were found at a depth of 10 m. At station 2, there were 3 colonies at a depth of 3 m, and 6 colonies at a depth of 10 m. Station 3 comprised 38 colonies at a depth of 3 m and 56 colonies at a depth of 10 m. The branching corals (CB) consisted of 129 colonies distributed as follow: station 1 had 2 colonies located at a depth of 3 m, while station 2 contained 12 colonies encountered at a depth of 10 m. Station 2 contained a single colony located at a depth of 3 m. At a depth of 10 m, no coral development forms were observed. Station 3 housed 89 colonies at a depth of 3 m and 25 colonies at a depth of 10 m. Massive coral (CM) populations consisted of 63 colonies distributed as follows: station 1 had 3 colonies at a depth of 3 m and 1 colony at a depth of 10 m. There was no detectable coral development at station 2. However, at station 3, there were 2 colonies at a depth of 3 m and 57 colonies at a depth of 10 m.

The growth type of coral colonies can offer distinct insights into the state of the aquatic environment in a certain region (Paulangan et al 2019b; Najmi et al 2022; Gastoldi & Cinti 2023). This outlines a categorization of the correlation between coral development types (biological entities) and the adjacent aquatic environment, specifically: first ruderals (r) refer to corals that readily acclimatize to their surroundings or promptly recover from harm, such as *Acropora* corals, which exhibit rapid growth, but possess a susceptibility to breakage. A second competitor (K) is a non-*Acropora* shaped coral with foliose and branching structures that dominates a body of water and exhibits fast growth. Thirdly, there are corals species that possess the capacity to resist stress, known as stress tolerators (S). These include both large and sub-massive corals that can endure both sedimentation and aquatic eutrophication.

Table 1 indicates that *Acropora* branching corals, characterized by their twig-like structure, are frequently located at station 3.

Station 3 exhibits strong currents, resulting in a dominance of *Acropora* species in this area. The branching structure of *Acropora* mitigates the effects of strong waves and ocean currents by distributing the forces experienced throughout the structure, thus reducing the likelihood of branch breakage (Rogers & Ramos-Scharrón 2022; Kolibongso et al 2024). Stations 1 and 2 are characterized by the prevalence of sheet-like corals (CF), branching corals resembling tree branches (CB), and creeping corals that are affixed to the substrate (CE), in contrast to station 3. The layout of the two stations is characterized by their proximity to the port and fish landing base (PPI), indicating a high density of location relative to the source. Factors such as pollution and fishing activities serve as stressors.

Table 1

Coral life forms found at all observation stations in the waters of Palopo City

No	Coral life form	*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	CE	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

Where: ACD - digitate *Acropora*; CF – foliose coral; CMR – mushroom corals; ACB – branching *Acropora*; CME – millepore corals; CE – encrusting corals; CB – branching corals; CM – massive corals.

Another source of stressors is sediment from river mouths near the observation station. Sediment significantly impacts coral reefs, influencing the health and sustainability of these ecosystems. For instance, sediment alters the structure of coral reef habitats by modifying the composition and distribution of resident species (Richmond et al 2019; Eddy et al 2021; Bitterwolf et al 2024; Dela Cruz & Harrison 2024). Additionally, sediment reduces sunlight penetration in the water, disrupting the photosynthesis process of coral symbionts (Rogers & Ramos-Scharrón 2022). The predominant sheet-like coral at station 1 is *Merulina ampliata*. CE identified at station 2 is *Leptastrea transversa*. The two types of coral are classified as K and S due to their significant adaptability to sedimentation, specifically by secreting mucus that inhibits sediment from infiltrating their polyps (Hanapiah et al 2019). The *Merulina* corals exhibit a colony morphology characterized by a branching structure, which facilitates load distribution and mitigates damage from strong ocean currents or shifting sediments. This structure facilitates efficient acquisition of sunlight necessary for symbiotic photosynthesis, similar to various other corals. The morphology of the coral type *L. transversa*, which is typically rounded, results in a reduced accumulation of sediment on the colony's surface when compared to foliose corals.

The live coral cover in the seas of Palopo City varied between 0.65% and 15% per unit area. The Ministry of Environment's assessment decision (Decree of the Minister of State for Environment No. 4 of 2001 Regarding: Standard Criteria for Coral Reef Damage) classifies the status of coral reefs in the waters around Palopo City as either damaged or poor.

The percentage of viable coral cover is evidently influenced by varied conditions. Referring to Table 2, the hard coral cover percentages at station 1 are 0.65% at a depth of 3 m and 2.10% at a depth of 10 m. Similarly, at station 3, the hard coral cover percentages are 10.37% at a depth of 3 m and 15% at a depth of 10 m. The mortality rate of coral in the reservoirs of Palopo City is really high, specifically ranging from 65.46 to 84.06% (Table 2). The significant proportion of deceased coral is attributed to many primary processes that naturally occur in a continual manner. Field observations indicate that various stressors or risks, including sedimentation, increasing sea water temperatures, tourism activities, and damaging fishing practices such as the use of dynamite and potash, contribute to significant coral mortality. Furthermore, research by Mahmudin et al (2020) and Najmi et al (2023) indicates that the main causes of coral reef mortality in Indonesia's coastal and marine areas are marine tourism activities such as snorkeling and diving, sedimentation, and increased fishing activities using explosives. Marine coral reefs situated in close proximity to the coast provide a higher potential risk in comparison to island regions that are distant from major human activity (Sahetapy et al 2017). The impact of activities occurring on land on the existence of coral reefs includes disturbances in the reproductive system and recruitment patterns of corals, decreased growth and recovery of coral reefs, increased competition (from algae and sponges), increased coral diseases, and increased coral mortality. According to the data presented in Table 2, it is evident that the decrease in living coral due to environmental pressure will lead to a higher proportion of coral mortality in the waters of Palopo City. Additionally, this drop may potentially intensify the competition among coral species in the same waters.

Table 2

Percentage of live coral cover in the waters of Palopo City

No	*Cover type*	*Station*					
		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

Abundance, diversity index, uniformity and dominance of reef fish. 59 species from 14 families were identified in the reef fish census conducted at three research stations. The greatest coral fish population was observed at station 3 on the coast of Songka Beach, at a depth of 10 m, namely 0.864 ind m^{-2}. Conversely, the lowest fish population was recorded at station 2 on the coast of Labombo Beach, at a depth of 3 m, specifically 0.08 ind m^{-2}. The overall population of coral fish at the three research stations is somewhat modest, averaging a mere 0.41 ind m^{-2}. This is consistent with the limited live coral biomass at each observation station, where robust coral reefs provide optimal habitats for fish.

Within the fish population recorded at station 1 at a depth of 3 m, 66% were classified as major fish, 15% as target fish, and 19% as indicator fish. Similarly, at a depth of 10 m, 72% were identified as major fish, 23% as target fish, and 5% as indicator fish. At station 2, at a depth of 3 m, 50% of the fish were classified as major fish groups, 37% were target fish, and 13% were indicator fish. At a depth of 10 m, 62% were major fish groups, 23% were target fish, and 15% were indication fish. At station 3, at a depth of 3 m, 55% of the fish were classified as major fish groups, while 17% were shown as indicator fish and 14% were identified as target fish. At a depth of 10 m, 79% of the fish were classified as major fish groups, 13% as indicator fish, and 8% as target fish. This is consistent with the inspection of the main coral fish groups observed at three observation locations. As per the assertion made by Dimara et al (2020), the prevalence of numerous large fish groups is a characteristic feature observed in coral reef regions, where this particular group exercises significant dominance. Figure 3 shows that the predominant families of fish observed at stations 1, 2, and 3 were those belonging to the Pomacentridae and Labridae families.

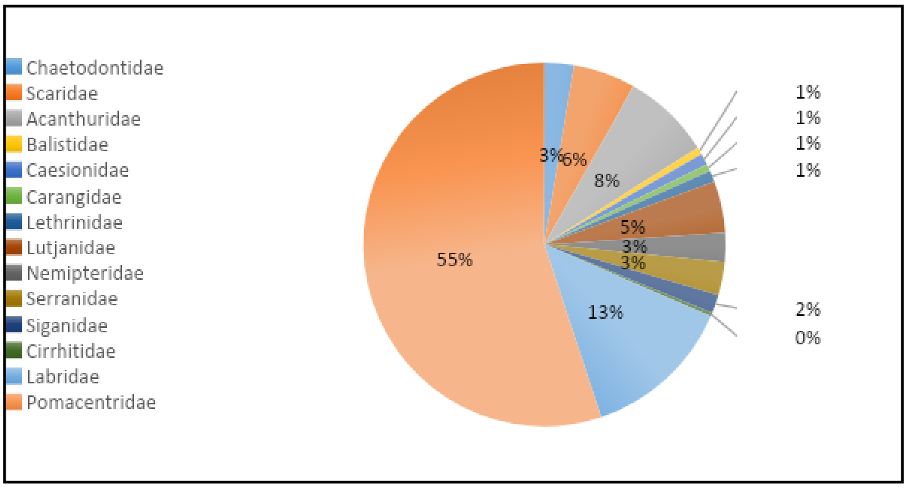

Figure 3. Abundance of coral fish in the waters of Palopo City.

The presence of Pomancentridae is significantly impacted by both living and non-living sources of substrate cover, as this family relies on the coral reef environment for sustenance. The study conducted by Ramadhani et al (2019) reveal that both living and non-living substrates have an impact on the geographical distribution and food retrieval locations. The Labridae family is found in Indonesian waters spanning from west to east, inhabiting diverse environments, resulting in various community structures (Wijanarko & Munasik 2013).

The coral fish diversity index (H') at the study station fell within the range of 0.93 to 2.751. At study stations with a depth of 3–10 m, the uniformity index (E) value falls between 0.709 and 0.906, while the dominance index runs from 0.095 to 0.486. According to the classification, the diversity index value falls within the low to medium range. The uniformity index value (E) indicates that the variety of coral fish present on the coast of Labombo Beach and Songka Beach is limited, and there is no prevalence of specific species in each distinct fish habitat within the coral reef ecosystem. This is evidenced by the consistently low dominance index values observed at all stations. The H' and E index values in the low category suggest that the surrounding environmental circumstances are unsuitable for the survival of coral fish, while values in the medium category indicate that the adjacent environmental conditions are suitable for the survival of coral fish. The coral fish ecological index can be seen in full in Table 3.

Table 3

Ecological indices of reef fish

Index	*ST 1*		*ST 2*		*ST 3*	
	3 m	10 m	3 m	10 m	3 m	10 m
H’	2.219	1.689	0.930	1.195	2.567	2.751
E	0.893	0.812	0.709	0.742	0.906	0.834
D	0.133	0.277	0.486	0.370	0.095	0.104

Note: H’ - diversity index; E - uniformity index; D - dominance index value.

The degree of diversity exhibited by a biota is inversely related to its degree of dominance. In habitats with low biota diversity, there is one or more species that exert dominance over that ecosystem (Armanto et al 2022). The dominance index (D) is a numerical value that varies between 0 and 1. A greater D value indicates a lesser amount of diversity in an ecosystem, as it correlates with the presence of dominant species. This assertion is substantiated by the findings of data collected from all observation sites, which indicate that the diversity index falls within the low to medium range. These low dominance index data indicate that no coral fish species dominates.

Coral reef management in Palopo City based on existing conditions. Coral reefs are crucial marine ecosystems that significantly contribute to marine biodiversity and serve to uphold ecological equilibrium, while also providing considerable economic support through the fisheries and tourism industries. Nevertheless, the degradation of coral reefs is a progressively concerning worldwide problem. Multiple causes, including both natural and human-induced variables, contribute to the deterioration of this ecosystem. The intricate nature of the causal connections between many elements that impact coral reef degradation in the waters of Palopo City can be elucidated by the use of a causal loop diagram (Figure 4).

The causal loop diagram illustrates that insufficient government coordination leads to greater damage to coral reefs, evidenced by a reduction in live coral cover and the degradation of ecosystems. The lack of optimal community empowerment is a contributing factor in this situation, highlighting the significance of local involvement in the management of coral reef ecosystems in the waters of Palopo City. The studies of Estradivari et al (2017) and Zekan et al (2022) indicate that conservation efforts for marine ecosystems, such as coral reefs, frequently fall short because of a lack of balance in local community involvement.

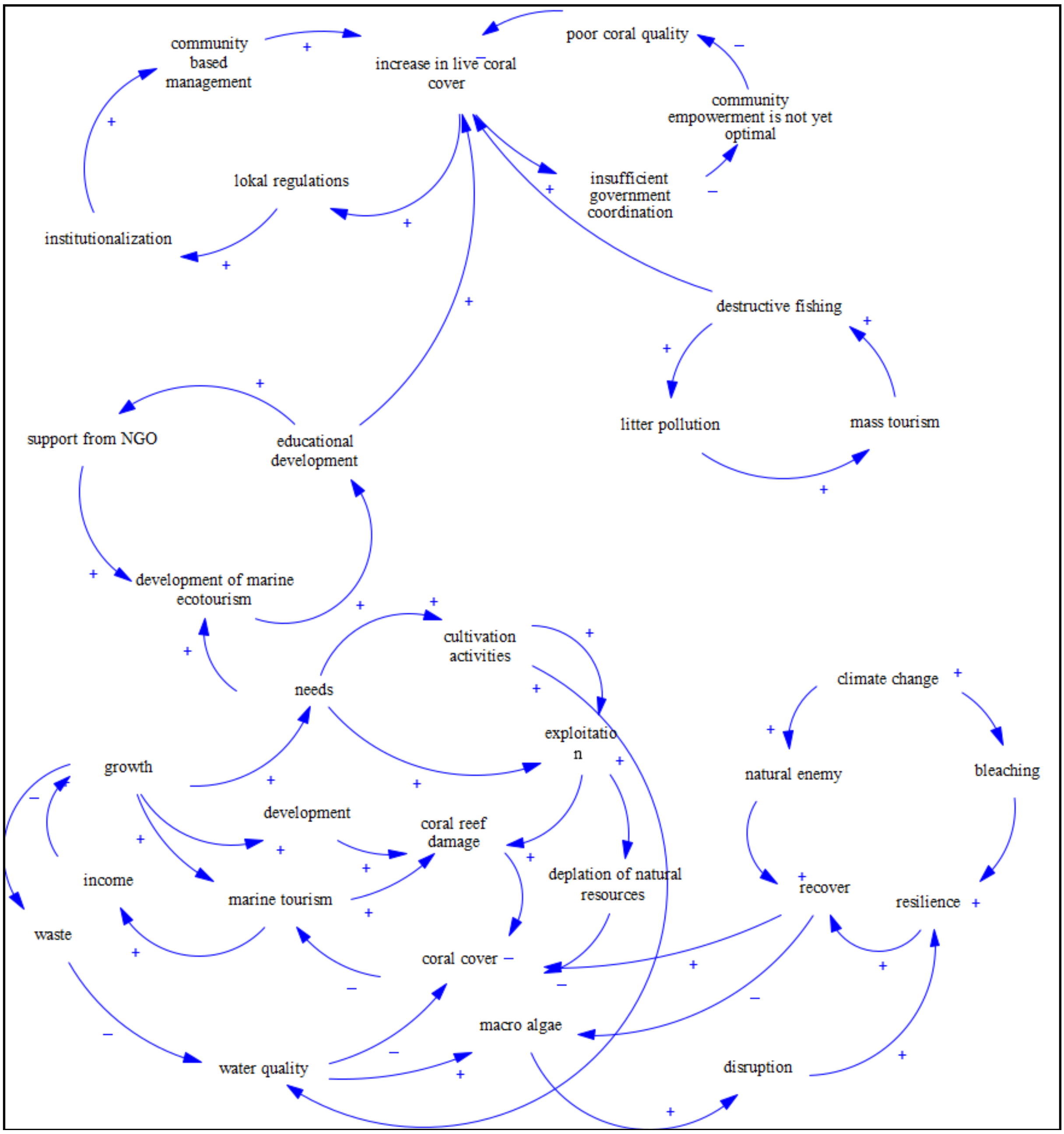

Figure 4. Causal loop diagram for coral reef ecosystem management in the waters of Palopo City.

The environmentally harmful fishing practices and the ongoing mass tourism approach in Palopo City are detrimental to the coral reef ecosystem. The two variables contribute directly to increased waste pollution and harm to the marine environment, leading to detrimental effects on coral ecosystems. The practices of overfishing and employing harmful fishing gear, like bottom trawl nets or fish bombs, can lead to the deterioration of coral reef habitats. Meanwhile, research by De et al (2020) explained that poorly managed diving and snorkeling tourism often leads to physical damage to coral from direct or accidental contact by tourists.

Regional development in the coastal regions of Palopo City frequently leads to a rise in the volume of waste that is discharged into the sea. The presence of wastewater, whether in solid or liquid state, has a detrimental impact on water quality, speeding up the deterioration of coral reefs. Research by Tuuri & Leterme (2023) indicates that waste not only contaminates water, but also leads to bioaccumulation in marine organisms, therefore impacting the food chain. Subsequently, the growing demand of humans for marine resources, both for economic and tourism purposes, has stimulated the growth of cultivation activities such as seaweed farming and floating net cages (KJA). Yet, if not controlled judiciously, these operations might worsen harm to coral reefs by generating more waste and reducing water quality (Mulyani et al 2018). The rising population in Palopo City exerts strain on the ecology due to the concurrent increase in demand for natural resources and land. BPS (2023) indicates that the population of the city was 177526 individuals in 2023. The population growth also contributes to the escalation of development activities in coastal regions, resulting in the degradation of coral ecologies. These findings align with the study conducted by Heery et al (2018). Furthermore, population growth exacerbates the deterioration of sea water quality, expedites the coral bleaching process, and diminishes the capacity of coral reefs to rebound from environmental disruptions. Moreover, intensified development activities in coastal regions include land reclamation, infrastructure development, and unsustainable tourism. Reef degradation in the waters of Palopo City is attributed to natural phenomena such bleaching and climate change, which have a direct impact on the well-being of coral reefs. Although humans cannot fully manipulate these variables, it is possible to implement mitigation and adaptation strategies to minimize their influence.

Priority strategies in coral reef ecosystem management. In order to select coral reef ecosystem management techniques in the waters of Palopo City, program planning was conducted using the Analytic Hierarchy Process (AHP) analysis. This involves synthesizing the relative importance of items in the AHP hierarchy in the form of criteria and policy choices. Effective management of coral reef ecosystems to facilitate integrated marine ecotourism has many strategic consequences, including enhancing the well-being of coastal populations and preserving resources. Management plans should provide due consideration to several significant factors, including ecological, economic, social, institutional, and technological aspects. This should involve incorporating the perspectives of stakeholders from local government agencies and community groups. By conducting pairwise comparisons for each ecological, social, economic, institutional, and technological criterion, the choice of coral reef ecosystem management in the waters of Palopo City is determined. The pairwise comparisons for each criterion indicate that the hierarchy of weights is as follows: ecological (0.322), technological (0.244), economic (0.185), social (0.140), and institutional (0.106) (Table 4).

Table 4

Scale of priority criteria in coral reef ecosystem management

Criteria	*Weight*	*Priority*
Ecology	0.322	1
Technology	0.244	2
Economy	0.185	3
Social	0.140	4
Institutional	0.106	5

The ecological criteria attain the highest ranking, therefore highlighting the significant influence of environmental sustainability factors in the management of coral reef ecosystems. The primary objective of ecosystem management should be to conserve biodiversity, maintain water quality, and maintain the integrity of the reef structure. An optimal ecosystem can guarantee the essential equilibrium required to sustain marine biodiversity. A literature review study by Hoegh-Guldberg et al (2019) found that robust coral reefs enhance ecological resilience to climate change and boost fisheries yield. Technological applications in coral reef management encompass satellite-based monitoring, coral reef rehabilitation, and technology aimed at mitigating the effects of climate change. Information technology plays a crucial role in identifying ecological changes and enabling prompt actions. Advanced technology applications encompass the utilization of satellite imagery for reef mapping and the deployment of drones for real-time monitoring of ecosystems (Nguyen et al 2021).

The economic dimensions are crucial in safeguarding that coral reef management also considers the financial viability for neighboring populations. Coral reef resources frequently yield economic advantages, including the facilitation of fishing and tourism. Optimizing the trade-off between economic advantages and environmental preservation is essential for attaining enduring sustainability (Nama & Akter 2020). Social dimensions encompass elements such as community engagement, indigenous knowledge of conservation, and educational initiatives. The active engagement of communities residing in close proximity to coral reef ecosystems in conservation and educational initiatives is vital to enhance their comprehension of the significance of coral reefs. Additionally, this guarantees that they are providing support for conservation initiatives in a manner that is environmentally sustainable. For successful policy, community knowledge and support serve as the fundamental pillars (Hudson et al 2019). Institutional frameworks encompass legislation, policies, and institutional capabilities that govern the administration of coral reef ecosystems. A robust institutional structure will guarantee a legal foundation that facilitates efficient and enduring administration. Lack of stringent controls can lead to overfishing, which can cause even more severe harm to the ecosystem (Kuemlangan et al 2023).

The priority strategy scores for managing coral reef ecosystems in the waters of Palopo City are derived from the weighting of the criteria. These scores are as follows: establish the zoning of coastal and marine areas with a score of 0.34, implement community-based management of coastal and marine areas with a score of 0.2633, promote environmentally friendly tourism with a score of 0.2386, and establish and divert destructive fishing gear with a score of 0.158. The comprehensive series of priority strategies for maintaining coral reef ecosystems is presented in Table 5.

Table 5

Priority strategies for managing coral reef ecosystems in Palopo City's waters

Alternative strategy	*Weight*	*Priority*
Determine the zoning of coastal and marine areas	0.3400	1
Community-based management of coastal and marine areas	0.2633	2
Development of environmentally friendly tourism	0.2386	3
Arrangement and diversion of destructive fishing gear	0.1580	4

Establishing the zoning of coastal and marine areas carries the greatest weight of 0.34 and is given the highest priority. As demonstrated by Sui et al (2020), regional zoning is crucial in coral reef management techniques as it safeguards ecosystems from excessive exploitation and enables more effective management by dividing regions according to conservation requirements and human usage. Community-based management of coastal and marine regions is assigned a weight of 0.2633 and is ranked as the second priority. This approach demonstrates the significance of engaging local communities in conservation endeavors. Community-based strategies can enhance the effectiveness of conservation efforts by using the indigenous ecological knowledge possessed by local communities, which can facilitate the adoption of sustainable practices (Dawson et al 2021; Esmail et al 2023). Research indicates that ecotourism, with a weight of 0.2386 and ranked as the third priority, can effectively contribute to the preservation of coral reefs. The practice of eco-based tourism serves to educate both the general public and tourists, while also offering economic incentives for conservation efforts (Samal & Dash 2023). The arrangement and diversion of harmful fishing gear, despite its relatively low weight of

0.1580 and being given the lowest priority, remains crucial. The method seeks to mitigate the detrimental effects of destructive fishing gear on coral reef ecosystems by implementing stringent regulations and replacing them with more ecologically sustainable fishing gear (Carneiro & Martins 2021).

Conclusions. Within the seas of Palopo City, the live coral cover ranges from 0 to 24%, indicating damaged or poor condition. The average coral fish abundance is 0.41 ind m^{-2}. One of the challenges in regional management is the degradation of coral reefs, mostly caused by fishing practices that remain unsustainable, such as the use of fish bombs. The government and the community are integral stakeholders in the management of coral reef ecosystems in the waters of Palopo City. Based on the findings of the Analytic Hierarchy Process (AHP) study, the objective is to establish the zoning of coastal and marine regions as the primary measure for preserving the sustainability of coral reefs. The recommended techniques are mutually supportive, with regional zoning being considered the primary basis, followed by community-based approaches and ecotourism, which have the potential to enhance conservation in the long run.

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 2023 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.

Conflict of Interest. The authors declare that there is no conflict of interest.

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Received: 16 September 2024. Accepted: 01 November 2024. Published online: 18 August 2025.
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How to cite this article:
Bibin M., Dema H., Damis, Halimah N., 2025 Sustainable coral reef ecosystem management model (Case study of Palopo City, South Sulawesi Province). AACL Bioflux 18(4):1924-1938.