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Assessment of coral reef health and resilience in Saobi and Sapapan Islands, Kangean Archipelago, Indonesia

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[2]Department of Biology, Faculty of Data Science and Analytics, Institut Teknologi Sepuluh Nopember. Jl. Teknik Kimia, Keputih, Sukolilo, Surabaya 60111, East Java, Indonesia

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Abstract. *Handoko A, Hidayah Z, Saptarini D, Wiyanto DB, Nurdini JA, Setiawan D, Vieira LDO. 2025. Assessment of coral reef health and resilience in Saobi and Sapapan Islands, Kangean Archipelago, Indonesia. Biodiversitas 26: 3545-3559.* Coral reef ecosystems in East Java are inadequately documented due to the lack of long-term monitoring and conservation programs, such as COREMAP, in comparison to the eastern region of Indonesia. This study aimed to assess the condition, conservation status, and resilience capacity of coral reef ecosystems on small islands. The research was conducted in the remote areas of Saobi and Sapapan Islands, situated to the east of mainland Madura Island, East Java, Indonesia. The percentage of benthic cover was measured in three stations on Sapapan Island and four stations on Saobi Island using the Underwater Photo Transect (UPT) method. The resilience of the coral reef ecosystem was evaluated by calculating the percentages of fleshy seaweed cover, rubble, and live coral cover. Also, the Conservation Class (CC) was determined by looking at the types of coral, which are categorized as Ruderals (r), Competitors (K), and Stress-tolerators (S) using the rKS ternary diagram. The results showed that based on the percentage of live coral cover, the benthic ecosystems of Saobi and Sapapan Islands are in moderate to excellent condition, with average live coral covers of 58.01±10.15 and 70.02±14.40, respectively. Coral lifeforms with a fairly high percentage and dominating the benthic habitat on both islands include Coral Branching (CB), Coral Massive (CM) and Coral Foliose (CF). Coral reef ecosystems in both islands showed a strong ability to recover, as shown by a high percentage of live coral cover and very little fleshy seaweed cover (3%) and coral rubble (60% or less). The rKS diagram showed that the coral reef ecosystems on Sapapan and Saobi Islands are classified as CC2 for conservation, meaning they have more than 60% Competitor-type coral (K) and over 50% live coral cover. These results suggest that the environmental conditions in the study area continue to support the coral reef growth.

Keywords: Conservation class, coral reef, resilience, ternary diagram

INTRODUCTION

Indonesia is in the center of Coral Triangle, an area with the highest marine biodiversity in the world. The Coral Triangle in Indo-Pacific has been acknowledged as the epicenter of coral diversity with over 500 species of stony coral (Ampou et al. 2018; Asaad et al. 2018; Davis-Reimer et al. 2022). Indonesia and five other neighboring countries, including Malaysia, Papua New Guinea, Solomon Islands, Philippines, and Timor Leste actively participated in a regional cooperation, known as Coral Triangle Initiatives (CTI) (Foale et al. 2013; Berdej et al. 2015). Despite covering only 1.6% of the world's oceans, Coral Triangle is home to 76% of known species, 37% of coral reefs fish species, 53% of the world's coral reefs (Veron et al. 2011).

Indonesian coral reef ecosystems span 32,000 km^2, with approximately 25,000 km^2 mapped by the Agency for Geospatial Information (Sawayama et al. 2015; Susanto et al. 2015). The most recent inventory conducted by Indonesian Institute of Science (LIPI) in 2017 showed that out of 1067 areas, 36.18%, 34.3%, 22.96%, and 6.56% were in poor, moderate, good, and excellent condition, respectively (Hadi et al. 2018). The inventory showed that the extent of coral reef damage in Indonesia was concerning and required substantial rehabilitation efforts (Mujahidah et al. 2023). Between 2009 and 2018, the global coverage of hard coral decreased from 33.3% to 28.8%, accounting for 13.5% of the total hard coral coverage worldwide (Souter et al. 2021). Substantial decline has been observed in various areas including Australia's Great Barrier Reef (GBR), Thailand, the Caribbean, and the Philippines (Osborne et al. 2011; Rioja-Nieto and Álvarez-Filip 2019; Paz-Alberto et al. 2021; Wolff et al. 2023). The primary factors contributing to coral reef's degradation include climate change, overfishing, habitat destruction, and pollution (Romero-Torres et al. 2020; Eddy et al. 2021; Zhu et al. 2022).

East Java Province, Indonesia, consists of 427 islands, including small islands with coral reef ecosystems (Hidayah et al. 2016). However, coral reef ecosystems of

East Java are poorly documented due to the absence of long-term monitoring programs (e.g., COREMAP). This study was carried out in a remote area of Saobi and Sapapan Islands of Kangean archipleago. Particularly, Saobi Island is a designated nature reserve for the endemic Gosong bird (*Megapodius reinwardtii*) (Suhardjono and Rugayah 2007). The Provincial Government has recommended some regions of the Kangean Archipelago as a Marine Protected Area (MPA) since 2018, with regard to their significant marine biodiversity. However, this policy has been challenged by insufficient data regarding the status of the coral reef ecosystem.

The predominant use of the resilience focuses on stability around a singular equilibrium state, highlighting resistance to disturbances and the rapidity of restoration (Holling 1996; Gunderson 2000; Nyström et al. 2008). Ecosystem resilience encompasses various concepts, including the ability to resist disturbances, reorganize, and maintain a diverse range of options for development and evolution (Holling 1996; Dakos and Kéfi 2022). The general definition of resilience for coral reef refers to their capacity to recover to their original state following disturbances (Nyström et al. 2008; Graham et al. 2013).

Previous research indicates that a coral reef ecosystem requires a significant amount of time to return to their original condition after experiencing damage (Ortiz et al. 2018; Roth et al. 2018; Mellin et al. 2019). Particularly for coral bleaching, the time needed to recover is around 9-12 years, provided that there are no additional disturbances such as cyclones or re-bleaching (Nava and Figueroa-Camacho 2017; Evans et al. 2020). The time required will be significantly longer when reefs are subjected to physical damage due to mining or blast fishing (Knowlton et al. 2021). This lengthy recovery process is related to the complex ecosystem dynamics and the specific conditions needed for coral growth (McClanahan et al. 2012; Dietzel et al. 2021; Zhu et al. 2022). Other studies emphasize that resilience of coral reef is influenced by aquatic environment, coral cover and composition, coral recruitment, herbivorous species, coral-eating organisms, and disease (Obura et al. 2011; Thompson et al. 2020; Bang et al. 2021). Due to the absence of long-term monitoring data and sea surface temperature record, other studies suggest that coral reef's resilience can be determined by the existence of specific benthic cover such as fleshy seaweed, live coral cover and rubble (Edinger and Risk 2000; Kulkarni and Saxena 2002; Giyanto et al. 2017). Comprehending the interaction of these factors helps in evaluating the health and recovery potential of certain reef systems (Viehman et al. 2018; Dietzel et al. 2021).

The common method to determine the conditions of coral reefs is by measuring live coral cover (English et al. 1997; Aunurrahman et al. 2024; Oetama et al. 2024). However, most of the studies are not followed by analysis that reflect the potential for coral reefs recovery after damage (Utama and Hadi 2018; Nugraha et al. 2020; Hidayat et al. 2023). This study provides a more comprehensive analysis that includes additional metrics to fully understand the recovery potential of coral reefs through classification according to the structural forms (Edinger and Risk 2000; Kulkarni and Saxena 2002). This study aimed to (i) assess live coral cover and composition in Saobi and Sapapan Islands; (ii) evaluate ecological resilience indicators and (iii) suggest conservation action. By examining both the condition and resilience capacity, this study is expected to contribute valuable analysis for effective management strategies in the natural reserve.

MATERIALS AND METHODS

Study area

This study was conducted from January to June 2024 on Sapapan and Saobi Islands. Both islands were included in Kangean Archipelago, Sumenep, East Java Province of Indonesia (Figure 1, Table 1). The coordinates of Sapapan Island are 06°58'30.45"S, 115°25'15.07"E, and those of Saobi Island are 06°59'10.35"S, 115°27'05.05"E. These islands are part of Kangean Archipelago which consists of 60 small islands with 27 being inhabited. The study area is approximately 135 km from the eastern tip of Madura Island or approximately 172 km from the northern part of Bali Island. Oceanographic conditions in the waters around Kangean Islands are greatly influenced by the conditions of the waters in the northern Bali Sea and Java Sea. The average sea surface temperature in the area during the western monsoon season ranges from 28-29 degrees Celsius (°C), but this value is lower in the eastern monsoon, at approximately 26.5-27°C (Susanto et al. 2022). These temperature variations are primarily driven by seasonal changes in ocean currents and wind patterns, which affect the distribution of warm and cold water in the area. Consequently, the fluctuations can impact local marine ecosystems and fisheries. Unique conditions in the western monsoon occur around the border of Bali Sea with Madura Strait, Java Sea, and Kangean Islands, where a pool of cold water occurs due to the upwelling phenomenon.

Table 1. Coordinate of observation stations

Islands	Stations	Latitude (S)	Longitude (E)	Description
Sapapan	SPP-1	06°57'31.89"S	115°24'59.33"E	The coral reef at this point is a fringing reef, located at a depth of about 5-8 meters. The distance from the coast is about 700 meters. The majority of coral reefs lie on a relatively flat seabed.
	SPP-2	06°57'32.80"S	115°24'49.98"E	
	SPP-3	06°57'34.80"S	115°24'42.34"E	
Saobi	SBI-1	06°58'12.83"S	115°27'38.55"E	As in the previous point, the type of coral reef is a fringing reef, but it is located in deeper waters of about 10-15 meters. The distance from the coast is about 500 meters with a seabed slope of approximately 2-5 degrees.
	SBI-2	06°58'25.74"S	115°27'11.28"E	
	SBI-3	06°58'20.98"S	115°26'48.62"E	
	SBI-4	06°58'40.26"S	115°26'13.95"E	

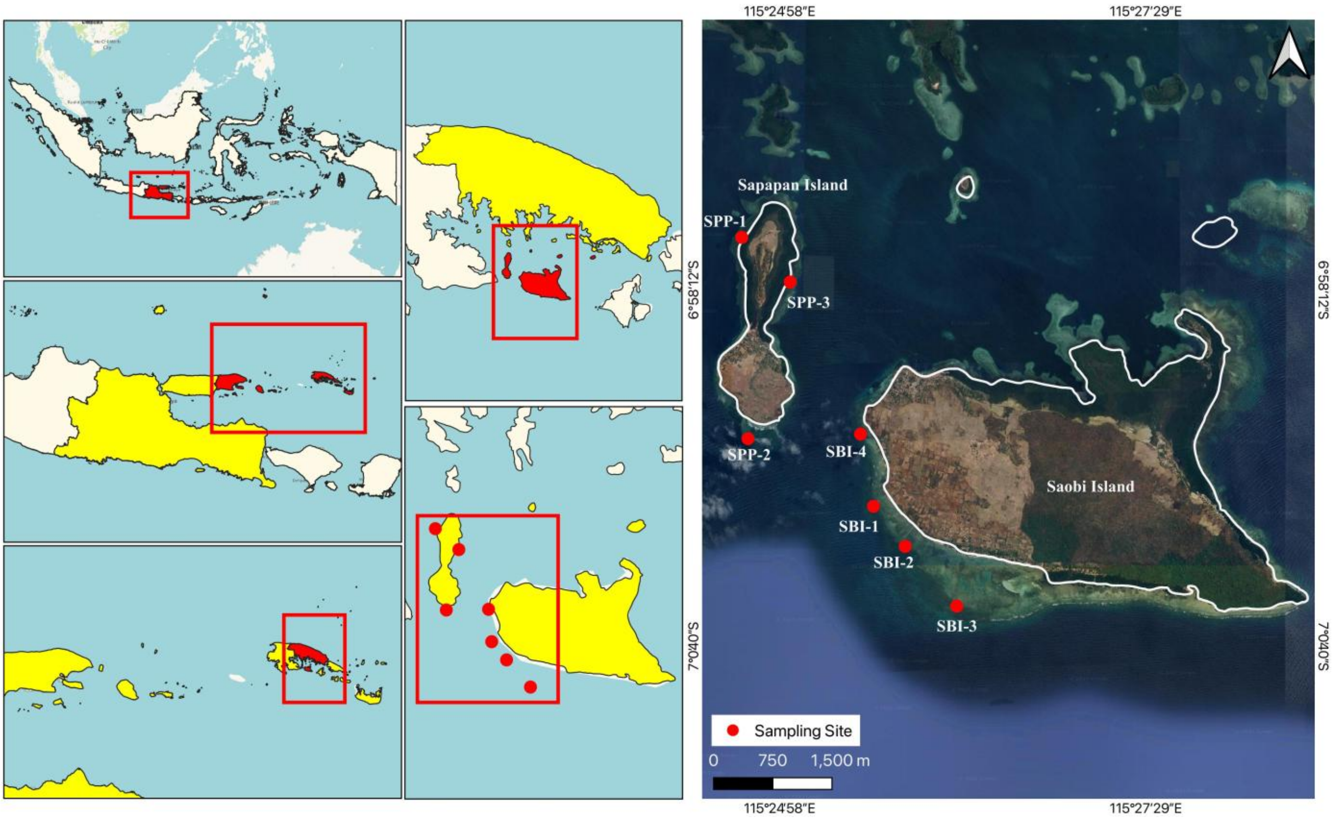

Figure 1. Study area Saobi and Sapapan Islands of Sumenep, East Java, Indonesia

Field data collection

Coral reefs data collection in the study was conducted at 7 stations, including three stations on Sapapan Island and four stations on Saobi Island. The determination of data collection stations is based on coral reefs distribution map obtained from the atlas map (https://allencoralatlas.org), which contains the world coral reefs cover. The Allen Coral Atlas is managed by the Arizona State University Center for Global Discovery and Conservation Science along with partners from Planet, Coral Reefs Alliance, and the University of Queensland, Australia. The Atlas uses high-resolution satellite imagery and advanced algorithms to map and track coral reefs around the world in unprecedented detail. Using this map facilitate the determination of the study area station to save time for area surveys. Table 1 shows the coordinates of each station.

Benthic environment and coral cover

Underwater Photo Transect (UPT) method was used to collect data on coral reefs and determine the health at each station (Jonker et al. 2008; Utama et al. 2022). Coral reef data collections were carried out at a depth of 4-6 meters. A 50-meter transect was stretched parallel to the coastline, and coral reefs data collection using a 58x44 cm^2 frame was carried out at each meter. The collection of coral reefs data was carried out from the 1st meter on the left side of the transect line, followed by taking photos at the 2nd meter on the right (Figure 2).

The UPT method was selected for this study due to its multiple advantages in coral reef monitoring. This method is relatively quick and straightforward, leveraging advancements in digital camera technology and computer software (Prasetya and Santoso 2022). Additionally, the data gathered in photographic form can be easily stored and compared for future monitoring efforts. Since data collection relies solely on photographs, the UPT method minimizes disturbance to coral reefs during the monitoring process (Kurniawan et al. 2024). Previous studies have indicated that the UPT method exhibits less variation and error compared to other techniques, such as Line Intercept Transect (LIT) and Point Intercept Transect (PIT), when assessing live coral cover (Prasetya and Santoso 2022; Teague et al. 2022; Irawan et al. 2023).

Furthermore, the resulting images of 350 data collections were analyzed to obtain the percentage of coral cover. This data was extracted from each photo by selecting 30 random point samples based on the type of benthic cover on the image. Each point was given a code that shows the life form category and then analyzed using CPCe (Utama and Hadi 2018) (Figure 3). This analysis allows the study to quantify the distribution of different life forms and substrate types in the images, providing valuable insights into ecosystem health and composition. The percentage of benthic cover is calculated based on the following formula (Gomez and Yap 1988):

$$L = \frac{\sum Li}{N} \times 100\%$$

Where, Li represents number of category points and N is refers to number of random points.

The results of the benthic category coverage, specifically live coral, were used to determine the health of coral reefs ecosystem. The condition of coral reefs ecosystem based on live coral coverage was divided into 4 categories (Gomez and Yap 1988), as shown in Table 2.

The morphological variation of each area was estimated as the diversity of coral morphology. This parameter was calculated as the diversity of coral morphology using the Shannon-Weaver formula as follows (Edinger and Risk 2000).

$$mH' = \sum -\left((p_i)(log_2 p_i)\right)$$

Where, m is morphology, H' is diversity index, pi is the proportion of coral colonies including morphology/life form-i. The criteria of the diversity index are H'≤1.0: low diversity, 1.0<H'≤3.0: moderate, and H'>3.0: high diversity.

Another measure of coral reef's deterioration is the quantity of dead corals discovered at the study area. The method of measuring Dead Coral (DC) was carried out concurrently with the percentage of Living Coral (LC) cover. Coral mortality index was measured using the following equation (English et al. 1997).

$$Coral\ Mortality\ Index = \frac{\%\ DC}{\%\ DC + \%LC}$$

Mortality index approaching zero shows that there is no significant change in living coral, while value one suggests a significant change in living to dead coral. According to English et al (1997), coral mortality index was divided into four categories, namely low (0-0.249), medium (0.25-0.499), high (0.50-0.749), and very high (0.75-1.00).

Coral reefs resilience index

Resilience factor is important to determine the ability of coral reefs ecosystem to recover after experiencing damage or a decline in condition due to natural events or anthropogenic factors. Resilience factor was calculated based on the percentage of fleshy seaweed, rubble, and live coral cover Giyanto et al. (2017). The description of each category is presented in Table 3.

Coral reefs conservation class

The determination of Conservation Class (CC) was based on the morphological composition of coral. At each area, the percentage of cover for each morphological category was calculated and normalized by the total living coral cover. The percentage data of live coral cover, as determined by the morphology and form of coral growth at each area, was used to generate Ruderals (r), Competitors (K), and Stress-tolerator (S) using the (rKS) ternary diagram, as shown in Figure 4.

The rKS ternary diagram was depicted based on the total cover of various coral morphological categories. This diagram assesses the tendency of coral community composition by examining the relative abundance of three primary coral morphologies, including ruderals, competitors, and stress-tolerator. The determination of CC can be categorized into three, as shown in Table 4.

Table 2. Coral cover category

Live coral cover (%)	Categories
0-24.9	Poor
25-49.9	Moderate
50-74.9	Good
75-100	Excellent

Table 3. Coral reefs resilience index categories

Categories	Description
Low resilience	Fleshy seaweed cover ≥3% or ruble cover >60% and living coral cover ≤5%
High resilience	Fleshy seaweed cover <3% or ruble cover ≤60% and living coral cover >5%

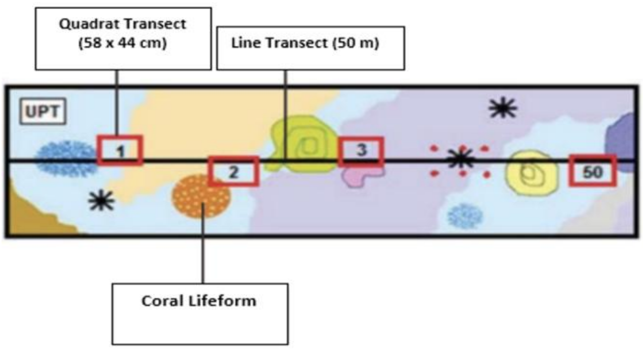

Figure 2. UPT method to collect data on coral reefs (Jonker et al. 2008; Utama et al. 2022)

Table 4. Ternary (rKS) triangle categories and Coral CC (Edinger and Risk 2000)

rKS categories	Conservation class	Dominant coral lifeform	% Cover
Ruderals (r)	CC 3	All kind of *Acropora*, Tabulate (non-*Acropora*), *Heliopora*, *Millepora*.	≥ 50%
Competitors (K)	CC 2	Non-*Acropora* (Branching, Plate, Foliose, Encrusting, free-living)	≥ 50%
Stress-tolerator (S)	CC 1	Coral Massive, Coral Submasive	≥ 60%

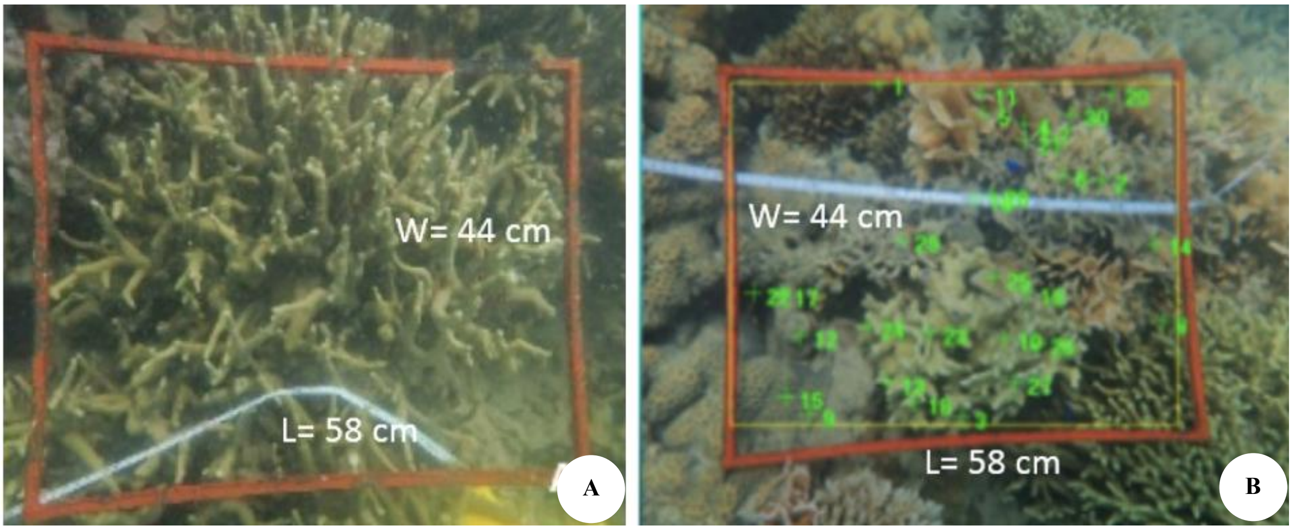

Figure 3. Underwater photo of coral lifeform of the study area in a 58x44 cm^2 frame. A. Original photo, B. CPCe software analysis

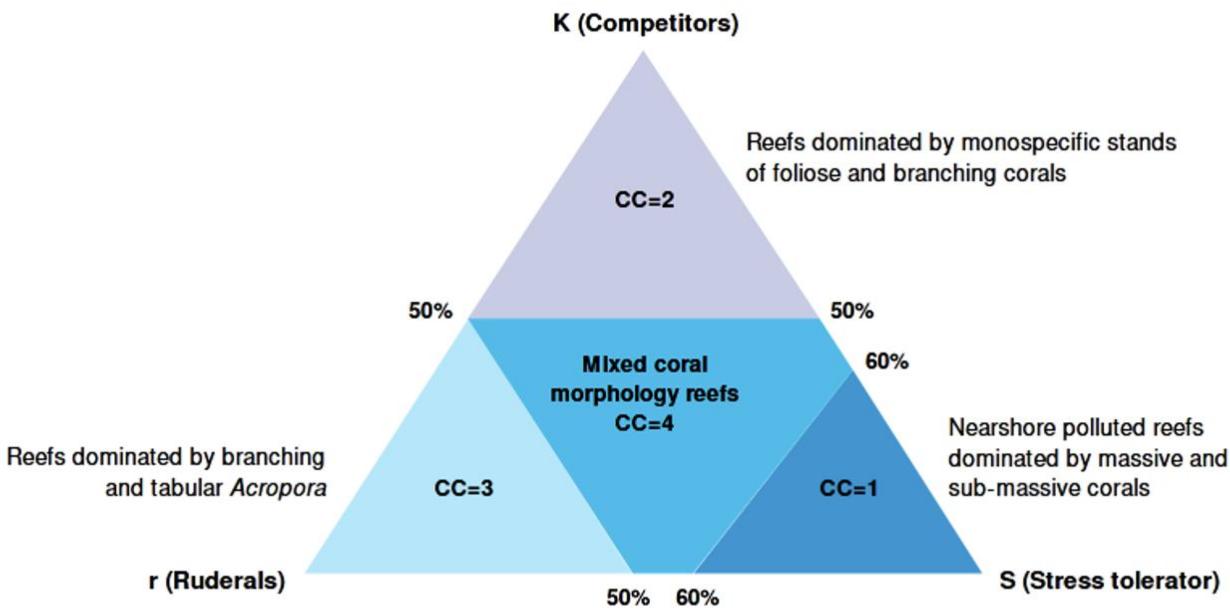

Figure 4. rKS ternary diagram for coral reefs CC (Edinger and Risk 2000)

RESULTS AND DISCUSSION

Coral diversity

Exactly 10 primary lifeforms that comprised coral reefs ecosystem on Sapapan and Saobi Islands were successfully identified through field data collection using UPT method. The following lifeform categories were present on the two islands, namely *Acropora Branching* (ACB), *Acropora Digitate* (ACD), *Acropora Submassive* (ACS), *Acropora Tabulate* (ACT), *Coral Branching* (CB), *Coral Encrusting* (CE), *Coral Foliose* (CF), *Coral Massive* (CM), *Coral Mushroom* (CMR), and *Coral Submassive* (CS). *Coral Branching* was the most dominant life form on Sapapan Island, comprising 63.53% of the total benthic cover, followed by *Coral Massive*, with a percentage of 9.53%. Meanwhile, *Coral Branching* and *Acropora Submassive* dominated coral reefs cover on Saobi Island, with cover percentages of 51.01% and 21.47%, respectively. Figure 5 shows the percentage of coral life form, whereas Tables 5 and 6 present the detailed identification of coral lifeforms discovered on every observation point of each island.

The variation of coral lifeform is influenced by natural factors, such as light levels, waves, and currents (Saptarini et al. 2017). *Coral Branching*, which dominates coral reefs cover at the study area, is a type of lifeform with rapid growth when supported by favorable seawater conditions. However, this lifeform is sensitive to environmental changes and strong currents that can lead to fragmentation

(Kangkan et al. 2023). *Coral Massive* is another prevalent lifeform often found in turbid littoral waters with elevated turbidity levels and subject to sediment resuspension. The dense and rock-like shape of massive coral leads to a greater accumulation of sediment due to the absence of a cavity that would allow sediment to travel through (Angkotasan et al. 2023). *Acropora Submassive* is the next dominant lifeform with the capacity to establish extensive colonies on reef plains and slopes in areas with moderate to high current velocity. In addition, Acropora corals are typically found in areas where waves break, and these species are capable of enduring currents and waves that flow toward the coast (Zamani and Maduppa 2011).

Further analysis identified 10 coral families and 24 genera in Sapapan and Saobi Islands (Figure 6), including Acroporidae, Agariciidae, Dendrophylliidae, Faviidae, Fungiidae, Mussidae, Pectiniidae, Pocilloporidae, Poritiidae and Siderastreidae (Table 7). Porites cylindrica was the most dominant coral genus at both study areas. This genus was characterized by a branching growth form with an arborescent shape and blends with the bottom. Corallites are very shallow, giving a smooth impression across the entire surface of the colony (Suharsono 2008). Another coral genus that was abundant at the study area was Acropora. The main characteristic of Acropora was the area of corallites on the radial and axial sides. Corallites are only present on the radial side of non-Acropora coral species (Suharsono 2008).

Table 5. Benthic coverage and coral lifeforms of Sapapan Island, East Java, Indonesia

Coral lifeforms	% Benthic cover		
	SPP-1	SPP-2	SPP-3
Acropora Branching (ACB)	0.07	1.07	0.00
Acropora Digitate (ACD)	0.07	0.00	0.07
Acropora Submassive (ACS)	1.93	2.00	4.53
Acropora Tabulate (ACT)	0.00	0.80	0.13
Coral Branching (CB)	46.33	53.73	63.53
Coral Encrusting (CE)	0.60	2.47	2.80
Coral Foliose (CF)	1.60	7.00	3.13
Coral Massive (CM)	1.27	9.53	1.67
Coral Mushroom (CMR)	1.07	1.07	0.93
Coral Submassive (CS)	0.73	1.20	1.00

Table 6. Benthic coverage and coral lifeforms of Saobi Island, East Java, Indonesia

Coral lifeforms	% Benthic cover			
	SBI-1	SBI-2	SBI-3	SBI-4
Acropora Branching (ACB)	0.67	1.67	0.00	5.53
Acropora Digitate (ACD)	0.13	0.27	0.00	1.07
Acropora Submassive (ACS)	4.13	21.47	8.13	1.73
Acropora Tabulate (ACT)	0.00	0.00	0.00	0.67
Coral Branching (CB)	24.60	38.20	51.07	31.07
Coral Encrusting (CE)	3.07	1.60	0.07	0.87
Coral Foliose (CF)	4.87	0.60	0.07	1.87
Coral Massive (CM)	8.07	1.33	1.53	3.87
Coral Mushroom (CMR)	0.60	1.80	3.40	2.67
Coral Submassive (CS)	0.40	0.60	1.07	3.13

Table 7. Coral families and genera found in Sapapan and Saobi Islands, East Java, Indonesia

Family	Genera	Sapapan Island			Saobi Island			
		SPP-1	SPP-2	SPP-3	SBI-1	SBI-2	SBI-3	SBI-4
Acroporidae	*Acropora*	√	√	√	√	√	√	√
	Anacropora	√	√	-	√	√	√	√
	Astreopora	-	√	√	-	-	-	√
	Montipora	√	√	√	√	-	-	√
Agariciidae	*Leptoseris*	-	√	-	-	√	-	√
	Pachyseris	-	-	√	√	-	-	√
	Pavona	√	√	√	-	√	√	√
Dendrophylliidae	*Turbinaria*	√	√	-	-	-	√	-
Faviidae	*Echinopora*	√	√	√	√	√	-	√
	Favia	-	√	-	-	√	√	√
	Favites	√	√	√	√	√	√	-
	Goniastrea	√	-	√	-	√	√	√
	Leptastrea	-	-	-	√	-	-	√
	Montastrea	-	-	-	√	√	-	√
	Platygyra	-	√	-	√	-	-	-
Fungiidae	*Ctenactis*	-	-	√	√	√	√	√
	Fungia	√	√	√	√	√	-	√
	Sandalolitha	-	-	-	-	-	√	-
Mussidae	*Lobophyllia*	-	√	-	-	√	-	√
Pectiniidae	*Oxypora*	-	√	√	√	-	-	-
Pocilloporidae	*Seriatopora*	-	-	-	√	√	√	√
	Stylopora	-	-	-	-	√	-	-
Poritiidae	*Porites*	√	√	√	√	√	√	√
Siderastreidae	*Psammocora*	-	-	-	-	-	-	√

Note: √: Present, -: absent

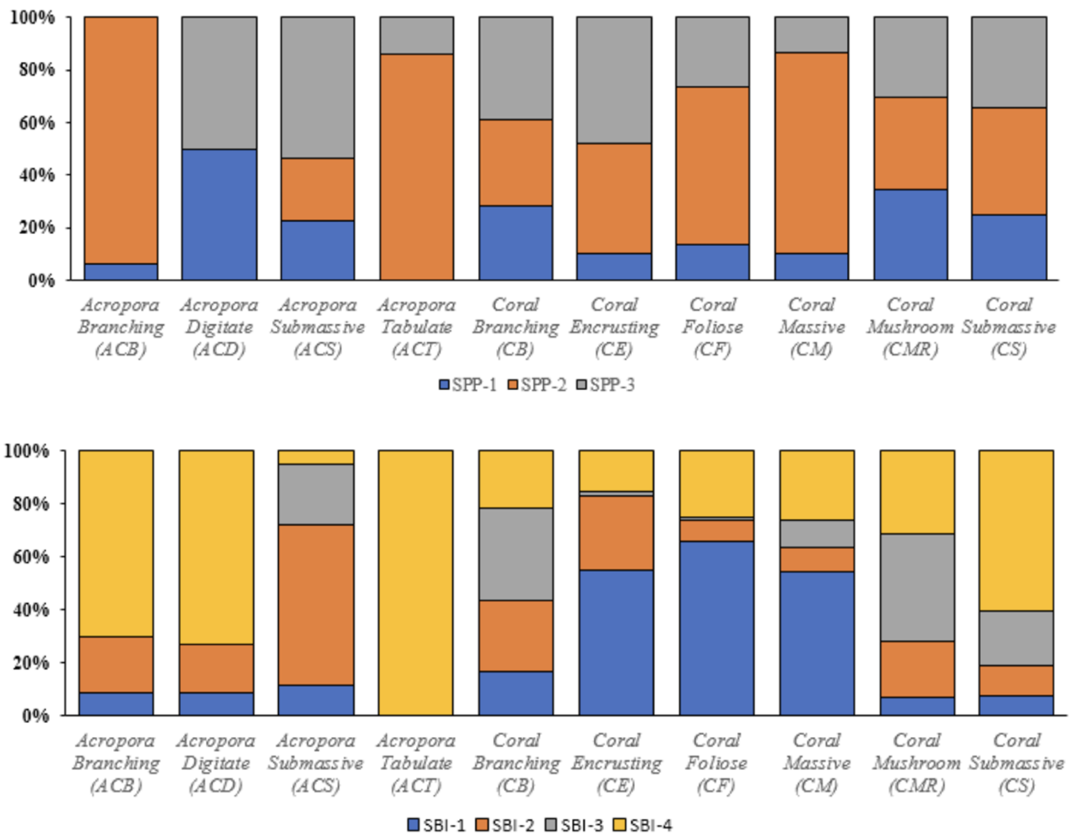

Figure 5. Percent cover of coral lifeform in Sepanjang (SPP) and Saobi (SBI) Islands, East Java, Indonesia

The diversity of coral morphology (mH) was calculated using the Shannon-Weaver index to infer habitat complexity at each area (Mann-Whitney U-test, p-value <0.05). The mH values of SPP-1 and SPP-3, on Sapapan Island, were 0.64 and 0.79, respectively, and were classified as low diversity. SPP-2 showed moderate diversity, as evidenced by mH value of 1.16. Meanwhile, coral diversity on Saobi Island was classified as moderate at SBI-1, SBI-2, and SBI-4 (1.0<mH<3.0). SBI-3 was included in a low diversity category, with mH value of 0.78. Moderate diversity suggests that environmental conditions support the ecological survival of organisms, while a low diversity index shows that the environment is less suitable with minimal variation in coral morphology. This result shows that while the ecosystem can sustain a range of organisms, the limited diversity in coral forms may hinder the resilience and adaptability of the reef structure. Consequently, the health of the coral community may be at risk despite the presence of various species. However, some studies argue that a low diversity index does not necessarily equate to poor environmental health, as certain coral species can thrive in specific conditions and dominate the ecosystem (Plaisance et al. 2011; Noonan et al. 2012; Viehman et al. 2018). Furthermore, the dominant species may provide essential functions and stability, allowing the reef to maintain its integrity even with limited morphological variation (Perry et al. 2011; Harborne et al. 2017).

The assessment of coral reefs conditions on both islands was not solely dependent on the presence of live coral, but also on the abundance of dead coral. Results in Sapapan Island showed that the mortality index of SPP-2 and SPP-3 were classified as low, with a value of 0.13, and SPP-1 was classified as medium, with a value of 0.36. In Saobi Island, SBI-1, SBI-2, and SBI-4 were included in the medium category, and only SBI-3 was categorized as low with a value of 0.22. Further reports also showed that the abundant presence of Dead Coral with Algae (DCA) in benthic environment of both islands threatened corals, thereby compromising the survival.

Live coral cover

The most common indicator in assessing the condition of coral reefs ecosystems is the percentage of live coral cover (Table 8). The results from UPT showed that live coral cover on Sapapan Island was higher with a percentage ranging from 53.67% to 78.87%, with average 70.02±8.31% included in the good to excellent category. Meanwhile, in Saobi Island, coral cover was in the moderate to good category with a percentage reaching 45.63% to 67.53%, with average 58.01±5.07%. Statistically, there was no significant difference in live coral cover between the two islands (Mann Whitney U-test, p>0.05) (Figure 7). Even though these two islands were not situated in a Marine Protected Area (MPA), the ecosystem was still in an exceptional condition, as evidenced by the percentage of live coral cover.

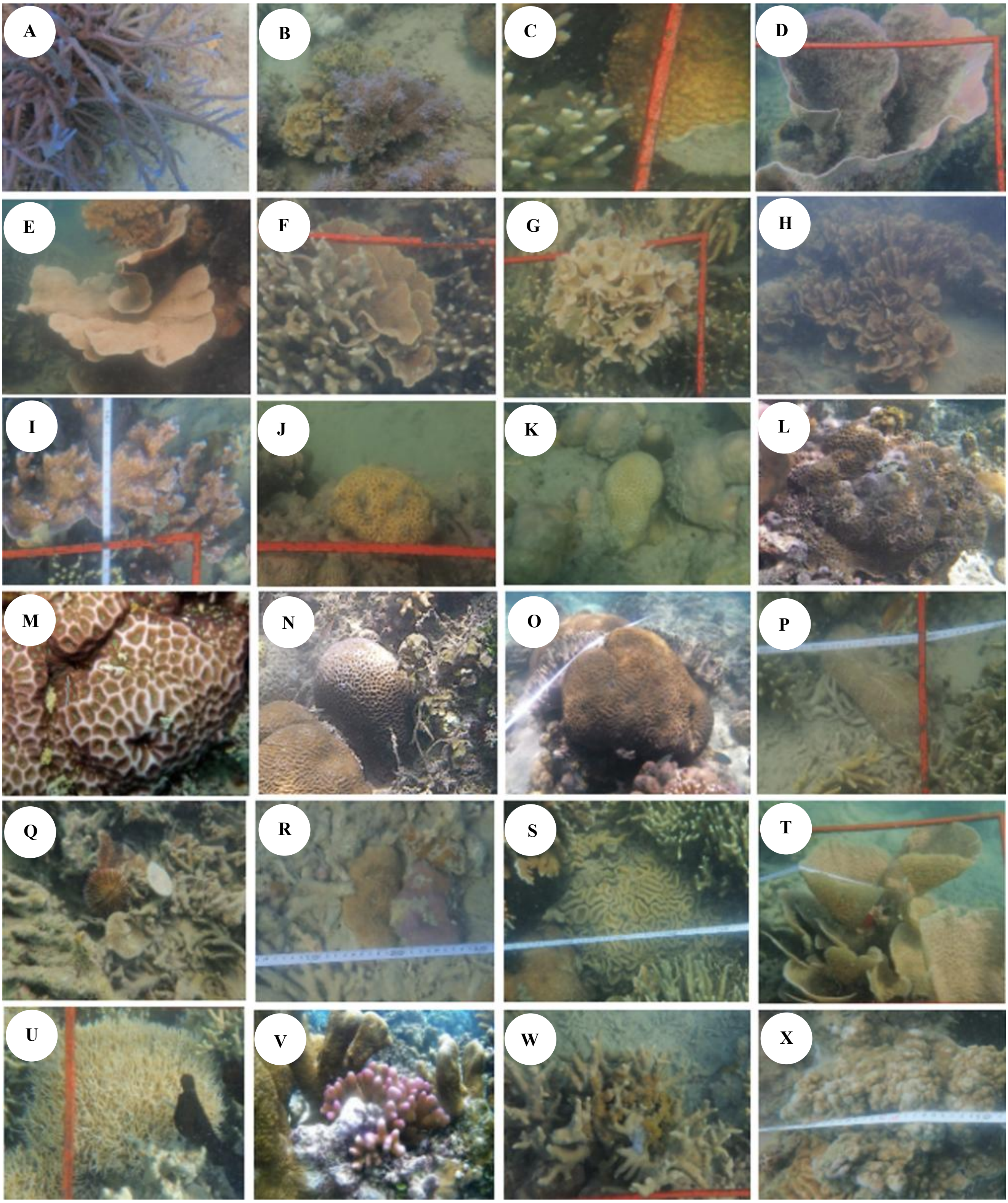

Figure 6. Coral genera found during underwater observation in Sapapan and Saobi Islands in East Java, Indonesia. Famili Acroporidae: A. *Acropora,* B. *Anacropora,* C. *Astreopora,* D. *Montipora*. Famili Agariciidae: E. *Leptoseris,* F. *Pachyseris,* G. *Pavona*. Famili Dendrophylliidae: H. Turbinaria. Famili Faviidae: I. *Echinopora,* J. *Favia,* K. *Favites,* L. *Goniastrea,* M. *Leptastrea,* N. *Montastrea,* O. *Platygyra*. Famili Fungiidae: P. *Ctenactis,* Q. *Fungia,* R. *Sandalolitha.* Famili Mussidae: S. *Lobophyllia*. Famili Pectiniidae T. *Oxypora. Famili* Pocilloporidae U. *Seriatopora,* V. *Stylopora.* Famili Poritiidae: W. *Porites*. Famili Siderastreidae: X. *Psammocora.* Source: Personal documentation and coral identification guideline according to Veron et al. (2024)

Coral reefs ecosystem at the study area exhibited improved conditions relative to several other areas, particularly in East Java. With an average live coral cover ranging from 57.96% to 70.02%, the ecosystem of these areas is in a better state compared to others, including Bangsring Banyuwangi, Paiton Probolinggo, Bawean Island, Sempu Island and other small islands in the Madura Strait (Hidayah and Wiyanto 2017; Saptarini et al. 2017; Nugraha et al. 2020; Hidayah et al. 2021; Isdianto et al. 2023). Further reports showed that live coral cover on Sapapan and Saobi Islands was higher than several other areas in western Indonesia, including Weh Island Aceh, Kepala Jeri Batam, and two MPAs, namely Karang Congkak of the Seribu Islands Jakarta and Moramo Bay of Taka Bonerate (Lelloltery et al. 2018; Utama and Hadi 2018; Mujiyanto et al. 2020; Sangaji 2022; Hidayat et al. 2023; Aunurrahman et al. 2024; Oetama et al. 2024). However, coral cover percentage of the two islands was slightly lower compared to other areas in Tanah Merah of Papua and Paladan Island of Central Sulawesi (Paulangan et al. 2019; Widodo et al. 2021). This result suggested that the study areas were performing well in terms of coral cover relative to many others in western Indonesia but did not reach the highest cover observed in areas, such as Papua and Central Sulawesi. In comparison to the national coral reefs state, the ecosystem of this study is part of the 22.4% included in good condition. Figure 8 shows recorded observations of live coral coverage across multiple areas in Indonesia.

The health condition of coral reefs with live coral cover indicators is highly dependent on natural conditions and the impact of anthropogenic activities. Global phenomena, such as increasing sea surface temperatures cause massive coral reefs degradation, leading to bleaching in many areas in Indonesia, particularly during 2015-2016. Meanwhile, human activities including environmentally unfriendly fishing methods concentrate coral reefs damage in specific areas. This global trend shows the vulnerability of coral reefs, reinforcing the importance of assessing resilience for areas, such as Saobi and Sapapan. Previous studies have shown that before the global bleaching in 2015, the percentage of coral reefs conditions that were fair and excellent continued to increase. However, since 2015, the percentage of poor coral reefs has almost doubled, increasing from 21% to 36% (Ampou et al. 2017; Kennedy et al. 2020). This is the result of warming sea temperatures flowing from the Indian Ocean every 3-7 years due to the natural activity of the El Niño Southern Oscillation (ENSO). The phenomenon shows the vulnerability of coral reefs to climate change and the cyclical nature of ocean temperature fluctuations (Wouthuyzen et al. 2018). The worsening conditions after 2015 show the urgent need for conservation efforts to protect these important ecosystems.

Coral reefs resilience and conservation status

The ability of coral reefs to survive environmental pressures is determined by two characteristics, namely sensitivity and resilience. Sensitivity refers to the ability to withstand environmental stressors without collapsing. Resilience, also known as recovery potential, refers to the ability to reconstruct structure and function after destruction (Thompson et al. 2020; Sangaji et al. 2024). The higher the level of resilience, the faster the coral reefs ecosystem recovers. This interaction between sensitivity and resilience is critical for coral reefs sustainability because it determines the response to pressures, particularly climate change, pollution, and anthropogenic factors. Resilience of coral reefs ecosystem in Sapapan and Saobi Islands was assessed by two primary indicators, namely fleshy seaweed, and unconsolidated rubble cover in benthic habitats.

Fleshy seaweed is a term for a group of observable algae, such as *Sargassum*, *Padina*, and other macroalgae. The denser the fleshy seaweed cover, the lower the level of resilience of coral reefs ecosystem (Edinger and Risk 2000). This is because the increasing cover of fleshy seaweed can obstruct coral growth. Dense algae growth may hinder coral larvae settlement and establishment of new coral colonies, potentially impeding coral reefs recovery (Cameron and Harrison 2020). In addition, seaweed growth outperformed corals in terms of space competition (Adiwijaya 2021). Strong waves or the use of explosives for fishing can destroy reefs and result in unconsolidated rubble. According to a previous study, the probability of recovery for coral reefs ecosystem diminishes with an increase in coral rubble (Kenyon et al. 2023). This is because coral rubble is very difficult to grow back as it is turned over by currents and waves, thereby causing an unstable substrate not suitable for the growth and development of coral larvae.

Table 8. The percentage of live coral coverage of Sapapan and Saobi Islands, East Java, Indonesia

Islands	Station	% Cover	Categories
Sapapan	SPP-1	53.40	Good
	SPP-2	78.87	Excellent
	SPP-3	77.80	Excellent
Saobi	SBI-1	46.53	Moderate
	SBI-2	67.53	Good
	SBI-3	65.33	Good
	SBI-4	52.47	Good

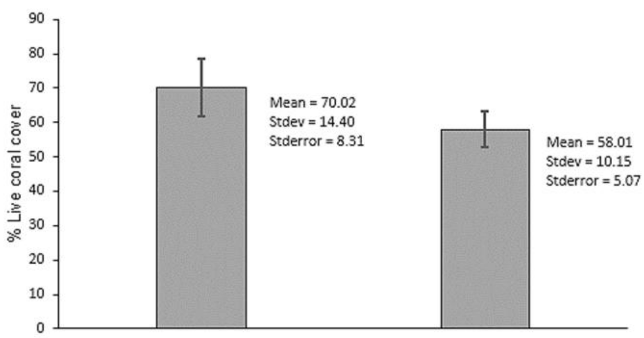

Figure 7. Comparison of % live coral cover of Sapapan and Saobi Islands, East Java, Indonesia, showing no significant difference (Mann Whitney U-test, p>0.05)

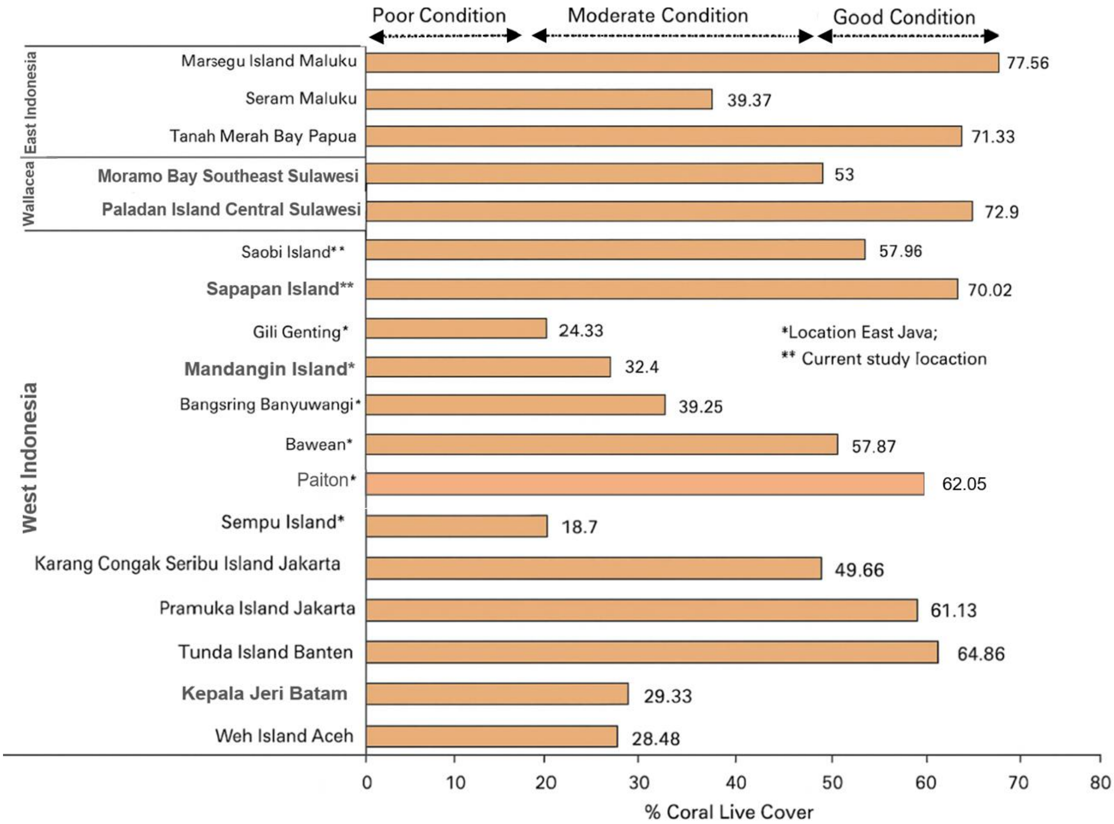

Figure 8. Percentage of live coral cover from different locations in Indonesia (2017-2024)

The high perc entage of live coral and minimal fleshy seaweed cover (<3%), as well as coral rubble (≤60%) across all observation stations on Sapapan and Saobi Islands suggest that the ecosystem exhibits a strong capacity for recovery (Figure 9). However, the actual recovery rate depends on how quickly coral symbiosis with zooxanthellae can be restored (Zamani and Maduppa 2011). Some studies showed that even with high resilience indicators, coral reefs were still vulnerable to external stressors, such as climate change and pollution (Harborne et al. 2017; Harvey et al. 2018; Wouthuyzen et al. 2018). The presence of minimal fleshy seaweed and coral rubble might also not be sufficient to sustain long-term health when other environmental factors remain unfavorable. A high percentage of live coral cover is also crucial for resilience of coral reef ecosystems. When live coral cover is abundant, nutrient content, natural processes within the food chain, and coral recruitment are at their optimal levels. In contrast, low percentage of live coral cover negatively impacts the entire ecosystem. Diminished habitat availability due to reduced live coral cover leads to a decline in the number of supported marine organisms (Schoepf et al. 2023). Furthermore, coral reefs play a vital role in nutrient cycling in the marine environment. Significant changes in live coral cover can disrupt these essential processes, potentially affecting the overall productivity and health of the ecosystem (Robinson et al. 2024).

Based on rKS ternary diagram classification, further analysis was carried out to determine coral reefs CC using three morphological characteristics. The diagram classified coral reefs ecosystem on Sapapan and Saobi Islands as conservation class 2 (CC2) (Figure 10). This was because the most common type of coral in the area is competitors (K), which includes Coral Branching, Coral Encrusting, Coral Mushroom, and Coral Foliose, with a total percentage of cover exceeding 60% (Table 9). Specific growth forms and strategies of competitive corals enable these species to occupy space and resources quickly. These corals expand rapidly, covering the available substrate, as well as having a distinctive form, such as branched, crusty, or leaf shaped. The distinctive forms enabled competitor corals to expand rapidly, occupy a greater amount of space and cover a wider substrate.

Table 9. Percentage of rKS Cover and CC

Areas	%Coral cover	% r	% K	% S	Conservation class
Sapapan Island					
SPP-1	53.40	3.85	92.42	3.73	CC2
SPP-2	78.87	4.90	81.49	13.61	CC2
SPP-3	77.80	6.08	90.49	3.43	CC2
Saobi Island					
SBI-1	46.53	10.60	71.20	18.20	CC2
SBI-2	67.53	34.65	62.49	2.86	CC2
SBI-3	65.33	12.45	83.57	3.98	CC2
SBI-4	52.47	17.15	69.51	13.34	CC2

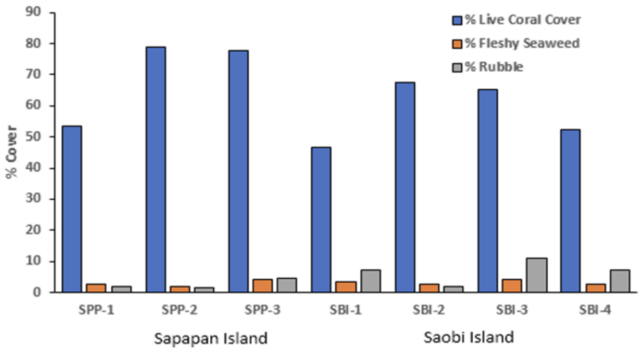

Figure 9. Composition of benthic habitat cover as indicators of coral reefs ecosystem resilience on Sapapan and Saobi Islands, East Java, Indonesia

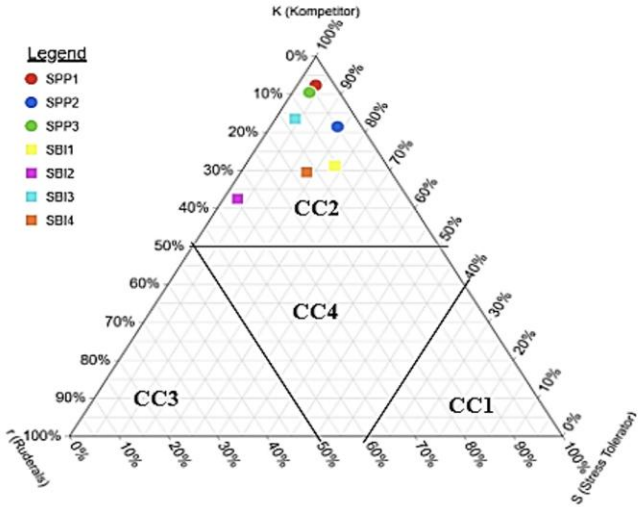

Figure 10. Ternary diagram presenting CC based on coral's morphological form

Coral reef ecosystems on Sapapan and Saobi Islands, classified as CC2, are characterized by competitor-type and live coral cover exceeding 60% and 50%, respectively, except for SBI-1 observation point (Figure 10). This result suggests that coral reef growth is still supported by environmental conditions with only minimal signs of ecosystem damage. Due to the remote area of the islands, land-based sedimentation and pollution were minimal, and no signs of cyanide or blast fishing were observed. These conditions facilitate conservation, as managers can focus on preventing future damage rather than mitigating existing degradation. The recommended action is to minimize anthropogenic activities that can increase environmental pressure on coral reefs. Local awareness of reef importance appears high (e.g., community-led no-fishing zones), which is a positive factor for conservation. However, the isolation of Sapapan and Saobi Islands limits the genetic diversity of coral species, which is crucial for resilience against climate change (Adam et al. 2022). Although local awareness is beneficial, external factors, such as climate change and ocean acidification continue to pose significant threats to this fragile ecosystem (Zamani and Maduppa 2011; Ampou et al. 2017; Wouthuyzen et al. 2018).

Coral reef ecosystems classified as CC1 require a more complex conservation initiative. The conditions of coral reef ecosystems in class CC1 were characterized by massive damages from land pollution and the effects of environmentally unfriendly fishing practices. Severely degraded coral reef ecosystems, stated as CC1 category, have limited potential to recover until the sources of pollution are removed (Birkeland 1997). Meanwhile, coral reef rehabilitation and protection efforts should concentrate on reefs in improved condition (CC2, CC3, and CC4), as these efforts tend to be successful (Edinger and Risk 2002; Kamarumtham et al. 2016). Coral reef ecosystems that have been mechanically damaged and are not subject to contamination may recover by being protected in a reserve supported by more active rehabilitation efforts, such as coral transplantation (Bowden-Kirby 1997; Edinger and Risk 2002). By focusing on healthier reefs, conservation efforts can maximize the impact and ensure a greater chance of recovery. This strategic method helps prioritize resources and enhances resilience of coral ecosystems.

The use of s ternary diagram to ascertain CC of coral reef ecosystem is highly beneficial in order to develop effective conservation strategies. The intended use of this diagram is to address the significant gap that occasionally happens between reef scientists and managers when developing rehabilitation strategies based on standard reef survey data (Edinger and Risk 2002). The diagram has also been associated with three factors that are beneficial for the preservation of coral reef, such as the number of species that inhabit the area, the number of uncommon species, and the complexity of the habitat, determined by the diversity in shapes and sizes (Edinger and Risk 2002). The combination of coral reef condition monitoring methods in conventional ways using line intercept transects or quadratic transects with ternary diagrams has been carried out in several areas in Indonesia and Malaysia, as shown in Table 10.

However, there are challenges associated with using morphological proxies of coral reefs, such as the rKS ternary diagram, which aims to represent the overall condition of an ecosystem in a specific area. While morphological proxies are useful for monitoring coral reefs, they have limitations. These include potential errors arising from significant factors, the difficulty of using data from individual coral colonies to evaluate the health of the entire reef, and the challenge of interpreting how shape changes relate to various stressors (Richards 2013; De Valck and Rolfe 2022). Furthermore, some morphological traits may not serve as reliable indicators of specific environmental changes (Zawada et al. 2019). Despite these limitations, morphological proxies can still offer valuable insights when combined with other monitoring methods. Integrating these traits with genetic or ecological data could enable researchers to achieve a more comprehensive understanding of reef health and resilience to stressors.

Table 10. Comparison of CC from different areas in Indonesia and Malaysia

Areas	% Live coral cover	Status	Conservation class	Source
Wakatobi National Park, Indonesia	23.9	Poor	CC1	Adimu et al. (2019)
	50.7	Good	CC2	
	48.7	Moderate	CC4	
Anak Datai Island Langkawi, Malaysia	36.75	Moderate	CC1	Ismail et al. (2022)
	37.01	Moderate	CC1	
	42.16	Moderate	CC1	
	51.22	Good	CC4	
Mertang Island Johor, Malaysia	52.26	Good	CC3	Ismail and Khoo (2019)
	48.35	Moderate	CC3	
	52.54	Good	CC4	
Tiomang Island Pahang, Malaysia	66.35	Good	CC3	Kamarumtham et al. (2016)
	50.07	Good	CC2	
	61.27	Good	CC4	
	63.08	Good	CC3	
Sapapan and Saobi Islands East Java, Indonesia	70.02	Good	CC2	Present study
	58.01	Moderate	CC2	

The results of this study showed that coral reef ecosystems on Sapapan and Saobi Islands were generally in good condition (upper-moderate to lower-excellent). Benthic habitat composition, characterized by a high percentage of live coral cover and minimal fleshy seaweed and rubble cover, suggests that the aquatic ecology is a healthy coral reef ecosystem with substantial recovery capacity coming after disturbances (Ortiz et al. 2018; Roth et al. 2018). Although the threat of anthropogenic activities to the sustainability of coral reef on both islands is minimal, massive damage can occur due to environmental changes, specifically rising sea surface temperatures that cause coral bleaching phenomena (Sully et al. 2019; Van Woesik and Kratochwill 2022). However, there have been no reported coral bleaching incidents in Kangean waters according to local environmental agencies. This lack of documented coral bleaching events suggests that other factors may be influencing coral health and coverage in the area. Therefore, further studies are needed to identify these potential stressors and the effects on the reef ecosystem of the islands.

All observation stations on Sapapan and Saobi Islands classified under CC2 category, confirmed that despite the excellent condition coral reefs ecosystem in this area, there is a need for conservation efforts. However, CC represented by ternary diagram should not be solely used for formulating conservation area policies. This strategy must be combined with other indicators related to further conservation objectives (Edinger and Risk 2000) due to the fact that coral reefs ecosystem in Indonesia is highly vulnerable to the effects of climate change (Hoegh-Guldberg et al. 2019). In this regard, resilience and mortality index were applied to enhance the results of ternary diagram. Resilience index was used to determine recovery potential of coral reefs. Mortality index was useful for determining the extent of coral reef damage and conservation efforts effectiveness (Edinger and Risk 2000). Conservation efforts are successful when there is a decrease in coral mortality rate. Conversely, when the mortality rate increases, evaluation and adjustment of conservation strategies are needed.

Furthermore, in a global context, coral reef ecosystems classified as CC2, which are in considerably healthy condition, provide a significant function as climate refugia in facing the threat of climate change. These refugia have the ability to provide protection against regional changes due to climate change, including the rise of ocean temperature and acidity. Also, they could develop an appropriate habitat for the growth and reproduction of diverse coral species and other marine organisms (Babcock 1991; Carpenter et al. 2008; Kavousi and Keppel 2018). Such refugia may increase the survival of corals and potentially enable their recolonization of degraded zones in subsequent years by acting as sources for coral larvae, thus potentially repopulating degraded areas after bleaching events (Kavousi and Keppel 2018; Dimitrijević et al. 2024; Sun et al. 2024). However, relying on refugia may not be a sustainable long-term solution, because human activities, such as pollution and fishing, can negatively impact the health and effectiveness of refugia (Andrello et al. 2022). Social and cultural approaches to conservation planning should be prioritized to raise awareness among fishermen regarding the dangers associated with environmentally harmful fishing methods for coral reefs. It is also recommended to explore safer alternative fishing techniques and income diversification strategies, such as the management of marine tourism areas.

Over the past two decades, coral reef ecosystems of Indonesia have suffered significant degradation due to global climate change and local pressures. Strategic initiatives are presently implemented to rehabilitate deteriorated reefs through various active restoration methods. The implementation of artificial reefs, with hazard mitigation strategies, such as enhanced water quality, the prohibition of blast fishing, and climate change protection, was expected to significantly contribute to the management of these complex ecosystems (Razak et al. 2022; De Clippele et al. 2023). Adaptive management strategies may be required to mitigate the short-term and long-term adverse impacts of coral reefs degradation. This requires more comprehensive management strategies, enhanced collaboration, and most importantly, increasing the participation of local communities in protecting marine environment.

In conclusion, coral reef ecosystems on Sapapan and Saobi Islands were classified as moderate to good, with an average live coral cover of 70.02±14.40% and 58.01±10.15% respectively. The low percentage of fleshy seaweed cover and coral rubble at all observation stations showed that coral reef ecosystems had a substantial resilience capacity. In addition, the presence of Competitor-typed coral (K) and live coral cover exceeding 60% and 50%, respectively suggested that coral reef ecosystems on Sapapan and Saobi Islands were classified as CC2. This result showed that the growth was still supported by environmental conditions with a minimum level of ecosystem damage. The classification indicated that these coral reefs were not only healthy but also capable of thriving despite minor disturbances. Resilience played a crucial role in preserving biodiversity and maintaining ecological balance in the area. While the coral reefs on both islands were not threatened by anthropogenic activities, the rise in sea temperature due to global warming posed a significant concern. This increase in temperature could lead to coral bleaching, which would weaken coral ecosystems and disrupt marine life. Conducting periodic surveys and assessments of the coral reefs' condition in the area is essential for developing an effective conservation strategy to ensure the sustainability of this vital marine ecosystem. Given the high resilience and CC2 status, we recommend including Saobi and Sapapan in East Java's Marine Protected Area (MPA) planning framework. In addition, to maintain the long-term sustainability of coral reef ecosystems in both islands, East Java provincial governments need to collaborate with local communities to intensify community-based monitoring programs on a regular basis.

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