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Monitoring Trends in Coral Reef Health: A Spatio-Temporal Study (2021-2024) (Case Study: National Conservation Area Policy of Pieh Island and Surrounding Seas), West Sumatra Province, Indonesia

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ABSTRACT

Coral reefs are vital marine ecosystems that provide significant ecological and economic benefits. However, increasing pressure from human activities and environmental changes threatens their sustainability. This study aimed to evaluate spatial and temporal trends in coral reef health in the Pulau Pieh National Conservation Area and its surrounding waters from 2021 to 2024. Data were collected using the Underwater Photo Transect (UPT) method and were analyzed with Coral Point Count with Excel extensions (CPCe) software. Key parameters assessed included live coral cover, algal cover, sand cover, and the Coral Mortality Index (IM). The results revealed spatial and temporal variations in reef condition, with some locations showing notable degradation attributed to both anthropogenic and natural stressors. These findings highlight the urgent need for adaptive, data-driven conservation strategies to ensure the long-term resilience of coral reef ecosystems.

INTRODUCTION

Coral reefs play a crucial role in marine ecosystems, serving as habitats for diverse marine species and acting as natural buffers that protect coastal areas from erosion and storm surges. Economically, these ecosystems are essential to coastal communities, supporting fisheries and marine tourism industries **(Eddy *et al*., 2021)**. However, coral reefs worldwide are experiencing significant degradation due to various anthropogenic pressures, including overfishing, pollution, habitat destruction, and climate change **(Razak *et al*., 2024)**.

One important strategy for protecting coral reef ecosystems is the establishment of marine conservation areas. In Indonesia, one such initiative is the Pulau Pieh Marine Tourism Park (MTP) and its surrounding waters in West Sumatra. This conservation area was formally established under the Decree of the Ministry of Marine Affairs and

Fisheries Number 38/KEPMEN-KP/2014, which outlines the management plan and zoning system for the period 2014–2034 **(Bahri, 2019)**. Covering 39,920 hectares, the zoning system is designed to balance ecological protection with sustainable resource use. It includes core zones (197.34 ha), limited utilization zones (39,681.10 ha), rehabilitation zones (25.01 ha), and port zones (16.55 ha), structured to address both ecological and socio-economic factors **(Sinaga *et al*., 2023; Fauzan *et al*., 2024)**.

The core zone is strictly protected for biodiversity conservation, while limited utilization zones are designated for controlled fishing, aquaculture, and marine tourism activities **(Oetama *et al*., 2024)**. The conservation area is managed by the National Marine Conservation Area Loka Pekanbaru, under the supervision of the Directorate General of Marine Space Management (Ministry of Marine Affairs and Fisheries of the Republic of Indonesia).

Pulau Pieh was designated as a conservation area primarily due to its rich coral reef ecosystem, with coral cover exceeding 70%. The area is dominated by fringing and patch reefs, which are not only ecologically important but also serve as major attractions for marine tourism. Additionally, the presence of reef fish, sea turtles, and cetaceans enhances its ecotourism potential. The limited utilization zones have thus become focal areas for sustainable marine tourism. However, to ensure both ecosystem preservation and the livelihoods of local communities, conservation efforts must be carried out with a long-term, sustainable approach **(Adimu *et al*., 2018; Aris *et al*., 2020; Muhtadi *et al*., 2020)**.

The effectiveness of the zoning system largely depends on the ability to manage anthropogenic pressures and maintain key biophysical parameters, such as live coral cover and the productivity of reef organisms. Recent studies have shown that coral reef conditions in the area vary spatially, influenced by differing environmental factors and human activity **(Mutaqin, 2020)**. Although some research has been conducted on aspects such as anchorage zones, tourism impacts, and fisheries **(Bahri, 2019; Yanti *et al*., 2023)**, there remains a lack of comprehensive, spatio-temporal studies comparing coral reef health across different zones.

Existing studies have often focused on isolated aspects—such as water quality or coral biodiversity—without fully integrating ecological changes over time **(Johan & Syam, 2015; Corvianawatie *et al*., 2018; Wouthuyzen *et al*., 2019)**. This limitation is often due to funding constraints, as large-scale environmental assessments require significant resources.

To address this gap, the current study adopts a spatio-temporal analysis approach to evaluate trends in coral reef health across the Pulau Pieh conservation area. Using the Coral Health Index (CHI)—which includes metrics such as live coral cover, algal cover, sand cover, and the Coral Mortality Index (CMI)—this research aimed to provide a more comprehensive understanding of reef ecosystem dynamics **(Zamani & Madduppa,**

2011). The findings are expected to serve as a scientific basis for improving coral reef management practices and informing adaptive conservation strategies.

MATERIALS AND METHODS

Data collection was carried out in the Pulau Pieh Marine Tourism Park (MTP) conservation area and its surrounding waters, located in West Sumatra Province, Indonesia, at coordinates 00°45′10″ – 01°03′08″ S and 99°59′36″ – 100°59′28″ E. This area is managed under a zoning system aimed at supporting the sustainable use of marine resources and ensuring long-term environmental protection **(Sinaga *et al*., 2023)**.

The MTP Pieh conservation area covers a total of 39,920 hectares and is divided into three main zones:

- **Core zone**: 197.34 hectares
- **Limited-use zone**: 39,681.10 hectares
- **Other zones**, including:
    - **Rehabilitation zone**: 25.01 hectares
    - **Port/anchorage zone**: 16.55 hectares

The core zone focuses on conservation efforts around five small islands: Bando Island, Pieh Island, Air Island, Toran Island, and Pandan Island. These zoning designations are intended to balance ecosystem protection, sustainable resource utilization, and environmental rehabilitation.

Monitoring was conducted at 16 research stations strategically distributed across the five islands and covering the three main conservation zones. The location of these research stations corresponds with established observation sites under the National Marine Conservation Area Management Office in Pekanbaru.

Further details regarding the spatial distribution of research stations are provided in Fig. (1) and Table (1).

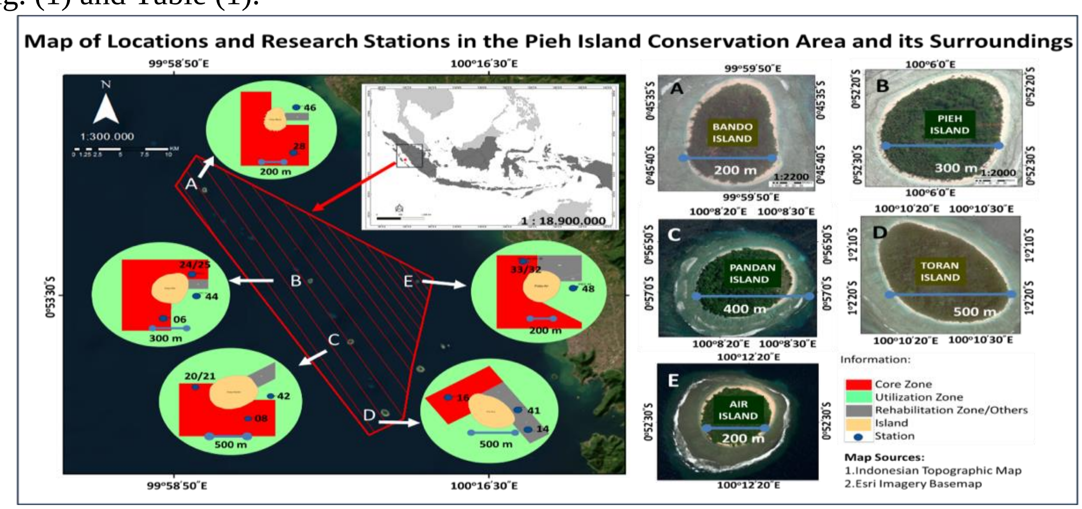

Fig. 1. Map of locations and research Stations in the Pieh Island Conservation Area and its surroundings

Table 1. Location of research stations and changes to station names and zones

Location	New Station	Zone	Longitude	Latitude
Toran Island	PIEC 14	Rehabilitation	100.178.028	-1.040.889
	PIEC 41	Rehabilitation	100.176.861	-1.037.194
	PIEC 16	Core	100,168972	-1,035556
Air Island	PIEC 32	Core	100,204444	-0,872944
	PIEC 33	Core	100,204444	-0,872944
	PIEC 48	Utilization	100.207.194	-0.874806
Pieh Island	PIEC 24	Core	100,102472	-0,872389
	PIEC 25	Core	100,102472	-0,872389
	PIEC 44	Utilization	100.102.694	-0.874611
Bando Island	PIEC 06	Core	100,100100	-0,877420
	PIEC 28	Core	99,998250	-0,764833
	PIEC 46	Utilization	99.998.722	-0.759139
Pandan Island	PIEC 20	Core	100,138611	-0,946722
	PIEC 21	Core	100,138611	-0,946722
	PIEC 42	Utilization	100.143.111	-0.950083
	PIEC 08	Utilization	100,141100	-0,952630

Water quality

Water quality assessment was conducted by measuring both physical and chemical parameters, including temperature (°C), pH, dissolved oxygen (mg/L), salinity (ppt), and brightness (m). These parameters were measured *in situ* at each observation station using a Water Quality Checker (WQC) to ensure accuracy and representativeness of field conditions.

The results were then compared against the Marine Water Quality Standards for Marine Biota as outlined in Government Regulation Number 22 of 2021, which serves as the benchmark for determining whether the water conditions fall within acceptable limits for sustaining marine life. The summarized comparison of measured parameters with regulatory standards is presented in Table (2).

Table 2. Water quality standards for marine biota

Parameter	Standard quality
pH	7 – 8,5
Dissolved oxygen DO (mg/L)	>5
Temperature (^{O}C)	28 – 30
Salinity (ppt)	33 – 34

Coral and benthic data

Data on benthic organisms—including coral species, substrate types, and associated benthic biota—were collected using the Underwater Photo Transect (UPT) method, following the guidelines established in the Coral Reef Monitoring Guide by **Giyanto *et al*. (2014)**. Data collection was carried out along a 50-meter permanent transect line, placed parallel to the shoreline at depths of 5 meters and 7 meters.

The UPT method employs an underwater digital camera and a transect frame measuring 58 x 44cm to capture images of the benthic community in photo format (Fig. 2). This method offers broader spatial coverage and greater time efficiency compared to manual visual observations.

Photographs were taken at 1-meter intervals along the transect, with the camera held perpendicular to the substrate at an approximate height of 60cm above the transect frame to ensure consistent image capture **(Wulandari *et al*., 2022)**.

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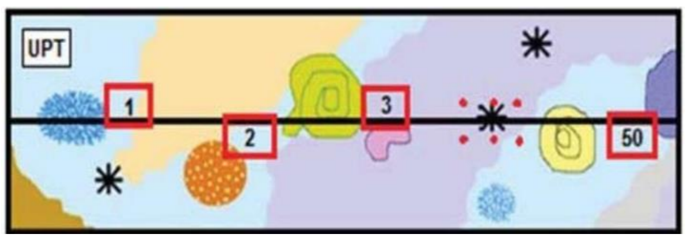

Fig. 2. Illustration of UPT method

The results of the photos taken from each station were analyzed using the CPCe 4.1 software to obtain quantitative data on benthic cover and coral identification **(Giyanto *et al*., 2017)**. CPCe is an efficient visual software for calculating coverage statistics from underwater photographs **(Utami *et al*., 2022)**. The analysis process includes determining the frame, overlaying random points, identifying benthic categories at each point, and storing the data in an Excel spreadsheet for further processing **(Nurrahman & Faizal, 2020)**. The identification of benthic categories was performed visually, based on guidelines from the Survey Manual for Tropical Marine Resources, Coral Finder Toolkit 3.0, and Corals of the World.

Identification using CPCe 4.1 generates data on benthic coverage, including coral, algae, and sand coverage. This software calculates the percentage of coverage based on the number of points that fall into a specific category in underwater transect photos. The calculations are done using the following formula:

$$\boldsymbol{Cover}\,(\%) = \left(\frac{\boldsymbol{n_i}}{\boldsymbol{N}}\right) \times \mathbf{100}\%$$

Where:
n_i : Number of points identifying a specific benthic category
N : Total sampling points in all transects photos.

Meanwhile, the Coral Mortality Index (CMI) is used to calculate the level of damage associated with the transition of live coral to dead coral. The index value ranges from 0 (no change in live coral) to 1 (indicating a change from live coral to dead coral) **(English**

***et al.* 1997)**. A higher CMI value indicates a greater level of coral degradation. The CMI was calculated using the following formula **(Zamani & Madduppa, 2011)**:

$$IM = \frac{DC}{LC + DC} \times 100\%$$

Where:

IM : Mortality index

DC : Dead coral cover (%)

LC : Live coral cover (%)

Assessment of coral reef condition

he assessment of coral reef condition relies not only on the percentage of live coral cover but also considers algal cover, sand cover, and the coral mortality index. The combination of these parameters provides a more comprehensive picture of the health of the coral reef ecosystem, making the assessment method more efficient, effective, and accurate **(Zamani & Madduppa 2011)**.

The results of the calculations for the percentage of live coral cover, algae, sand, and mortality index are compared against the coral reef health standards developed by **Zamani and Madduppa (2011)**, as shown in Table (3). This assessment criterion integrates several parameters—including live coral, algae, and the mortality index—to evaluate the condition of the coral reef ecosystem. High live coral cover typically indicates a healthy ecosystem, while high levels of algal or sand cover may suggest ecological stress caused by environmental disturbances. The coral mortality index also serves as an indicator of ecosystem degradation, where a higher value reflects increased coral death, potentially resulting from bleaching, sedimentation, or other anthropogenic impacts.

Table 3. Coral health condition assessment parameters

Parameter	**Assessment Criteria**			
	Very Good	**Good**	**Currently**	**Bad**
Live Coral Cover (%)	75 – 100	50 – 74,9	25 – 49,9	0 – 24,9
Algae Cover (%)	0 – 24,9	25 – 49,9	50 – 74,9	75 – 100
Pair Cover (%)	0 – 24,9	25 – 49,9	50 – 74,9	75 – 100
Mortality Index (IM)	0 – 0,249	0,25 – 0,499	0,50 – 0,749	0,75 – 1

RESULTS

Water quality

Water quality is a crucial factor that affects the health of coral reef ecosystems and the marine organisms that depend on them **(Wulandari *et al.*, 2022)**. Measurements of water quality parameters—pH, dissolved oxygen (DO), temperature, and salinity—were conducted *in situ* at 16 research stations from 2021 to 2024. The results were compared against seawater quality standards based on Government Regulation Number 22 of 2021.

According to Table (4), there were significant fluctuations in several key parameters that could impact marine life. In general, pH levels remained stable across all stations, averaging between 6.9 and 8.4 (with a range from 7.0 to 8.5), which does not threaten the chemical balance necessary to support aquatic organisms. In contrast, DO levels experienced drastic declines, particularly in 2021, 2023, and 2024, with values ranging from 0.8 to 4.9mg/ L—well below the minimum standard of > 5mg/ L. These low values indicate potential hypoxic conditions, which can disrupt the respiration of marine organisms and significantly increase mortality risk.

Conversely, in 2022, all stations recorded DO levels above 5mg/ L, suggesting a more optimal environment for marine life. These fluctuations in dissolved oxygen likely reflect external influences such as temperature shifts, changes in salinity, and anthropogenic activities that disrupt the biogeochemical cycles of the aquatic ecosystem **(Rositasari 2020)**.

Table 4. Water quality

St. (PIEC)	**pH**				**DO (mg/L)**				**Temperature (°C)**				**Salinity (ppt)**			
	2021	**2022**	**2023**	**2024**	**2021**	**2022**	**2023**	**2024**	**2021**	**2022**	**2023**	**2024**	**2021**	**2022**	**2023**	**2024**
14	8,2	8,4	8,1	8,1	3,6	7,4	2,0	4,6	29,0	30,0	30,0	31,8	33,0	30,0	32,0	36,8
41	8,1	8,4	8,2	8,0	3,7	7,5	2,3	4,6	30,0	30,0	30,1	31,9	34,0	32,0	32,0	37,2
16	8,2	8,4	8,1	8,0	3,7	7,4	3,8	4,3	30,0	30,0	30,5	31,7	33,0	32,0	31,8	37,6
32	8,0	8,4	8,2	7,9	4,0	8,4	2,3	4,1	29,0	30,0	30,2	31,8	42,0	32,0	31,9	40,5
33	8,2	8,4	8,2	8,1	3,7	7,5	2,3	3,9	29,0	30,0	30,0	31,9	42,0	33,0	31,9	40,7
48	8,2	8,4	8,1	8,1	4,2	7,4	2,2	4,3	30,0	30,0	30,1	31,9	43,0	31,0	32,0	39,0
24	8,2	8,4	8,3	8,1	4,2	7,4	3,8	4,9	30,0	30,0	30,5	31,6	42,0	34,0	31,4	39,9
25	8,2	6,9	8,3	8,1	4,2	2,1	4,1	4,8	30,0	30,0	30,7	31,6	43,0	25,0	31,4	39,9
44	8,1	8,4	8,0	8,1	4,5	7,4	3,2	4,9	31,0	31,0	30,5	31,7	43,0	32,0	32,1	39,6
06	8,2	8,4	8,3	8,0	4,7	8,4	3,9	4,8	31,0	30,0	30,6	31,6	43,0	30,0	31,3	37,7
28	8,2	8,3	8,3	7,8	3,5	7,3	3,2	3,6	30,0	30,0	30,2	32,0	34,0	31,0	31,8	40,1
46	8,2	8,4	8,1	7,5	3,7	7,6	3,2	4,1	30,0	30,0	30,4	32,2	33,0	31,0	31,6	39,3
20	8,2	8,4	8,1	8,0	4,1	7,4	2,3	0,8	28,0	30,0	30,0	31,3	33,0	30,0	32,1	36,7
21	8,2	8,4	8,1	8,1	4,1	7,7	2,4	0,9	28,0	30,0	30,1	31,6	33,0	31,0	32,0	36,3
42	8,2	8,3	8,0	8,1	3,7	8,2	3,2	1,1	30,0	31,0	30,5	31,7	34,0	31,0	32,1	36,9
08	8,2	8,4	8,2	8,0	3,5	7,3	2,4	3,5	29,0	30,0	30,6	31,1	34,0	34,0	31,5	35,5
Average	**8,2**	**8,3**	**8,2**	**8,0**	**3,9**	**7,3**	**2,9**	**3,7**	**29,6**	**30,1**	**30,3**	**31,7**	**37,4**	**31,2**	**31,8**	**38,4**
Standart	7 – 8,5*				>5 mg/L*				28 – 30ºC*				33 – 34 ppm*			

(**Source :** Government Regulation Number 22 of 2021)

Next, the parameters of temperature and salinity also experienced significant increases during the observation period. The average water temperature showed an upward trend, with several stations recording temperatures of 31.9°C in 2024, exceeding the standard range of 28– 30°C. The highest average temperature occurred in 2024, reaching 31.7°C, which can negatively impact the water's ability to retain dissolved oxygen **(Ali *et al.*, 2022)**. This rise in temperature poses a risk of hypoxia, threatening the survival of aquatic organisms and potentially triggering coral bleaching **(Mariu *et al.*, 2023)**.

Previous studies have also reported that sea surface temperatures in the Pieh Island Conservation Area range from 29 to 33.2°C, with minor annual fluctuations—yet still holding the potential to cause significant ecological impacts **(Fauzan *et al.*, 2024)**. Temperature is a critical factor influencing coral reproductive success, including processes such as gametogenesis and spawning **(Carlson *et al.*, 2022; Isdianto *et al.*, 2024)**.

Coral cover

Coral cover consists of various types of hard corals with diverse growth forms, reflecting the richness and complexity of coral reef ecosystems. Some of the coral types found include *Acropora Branching* (ACB), *Acropora Digitate* (ACD), *Acropora Encrusting* (ACE), *Acropora Submassive* (ACS), *Acropora Tabulate* (ACT), *Coral Branching* (CB), *Coral Encrusting* (CE), *Coral Foliose* (CF), *Coral Heliopora* (CHL), *Coral Massive* (CM), *Coral Millepora* (CME), *Coral Mushroom* (CMR), *Coral Submassive* (CS), and *Coral Tubipora* (CTU). Among these, *Acropora Branching* (ACB) plays a crucial role in the rapid recovery of coral cover but is highly vulnerable to both natural and human-induced disturbances. Therefore, the presence of branching corals should ideally be complemented by a higher abundance of massive (CM) and submassive (CS) corals, which indicate more stable water quality and greater resilience to environmental change.

Based on the data presented in Fig. (3), live coral cover across the 16 research stations showed significant variation from 2021 to 2024. Stations such as PIEC 8, 16, and 25 consistently recorded the highest coral coverage, peaking between 69.87 and 90.27% in 2023. This suggests that environmental conditions at these sites continue to support coral growth and exhibit high resilience. In contrast, stations like PIEC 14, 46, and 41 had relatively lower coral cover, although some of these showed intermittent improvements during the study period. Notably, PIEC 16 and PIEC 8 alternated as the stations with the highest annual coral cover, while PIEC 14 (in 2021, 2023, and 2024) and PIEC 46 (in 2022) consistently recorded the lowest coverage.

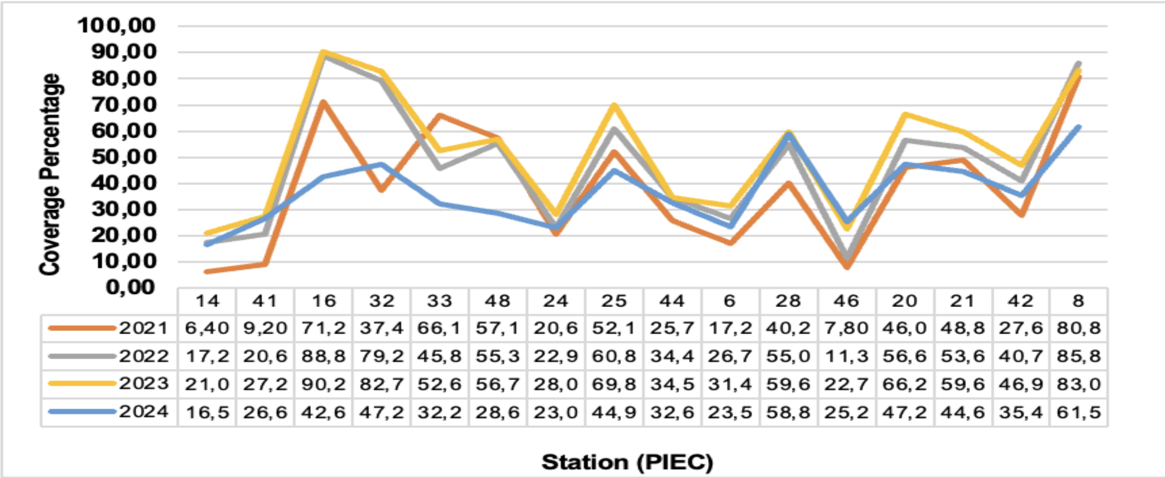

Fig. 3. Graph of the percentage of live coral cover at various observation stations in the Pieh Island Conservation Area from 2021 to 2024

The year-to-year trend indicates that most stations experienced a significant increase in coral cover between 2021 and 2023, followed by a sharp decline in 2024. For instance, PIEC 16 rose from 71.27% in 2021 to 90.27% in 2023. Similarly, PIEC 32 and PIEC 28 recorded notable increases—from 37.47% to 82.73%, and from 40.27% to 59.67%, respectively. This upward trend can be attributed to the recovery of coral reef ecosystems, improved conservation efforts, and favorable environmental conditions that supported coral regrowth.

However, in 2024, the majority of stations experienced a marked decline in coral cover, particularly PIEC 16, 33, 48, and 25. For example, PIEC 16 dropped sharply from 90.27% in 2023 to 42.67% in 2024, while PIEC 33 and PIEC 48 declined from 52.60% to 32.27%, and from 56.73% to 28.60%, respectively.

Algal coverage

Based on the algal coverage data from 2021 to 2024, as shown in Fig. (4), there is a varying trend among the research stations. Some stations exhibit a gradual decrease in algal coverage, while others experience significant fluctuations throughout the period. The stations with consistently high algal coverage between 2021 and 2024 are PIEC 14 and PIEC 41, which recorded initial values of 67.13 and 70.40% in 2021, with slight decreases to 66.00 and 63.13% by 2024. This trend indicates that algae in these locations have remained relatively stable despite minor fluctuations.

Conversely, PIEC 16 has undergone drastic changes, showing very low values in 2022 and 2023 (9.73 and 5.33%, respectively), before sharply increasing to 38.53% in 2024.

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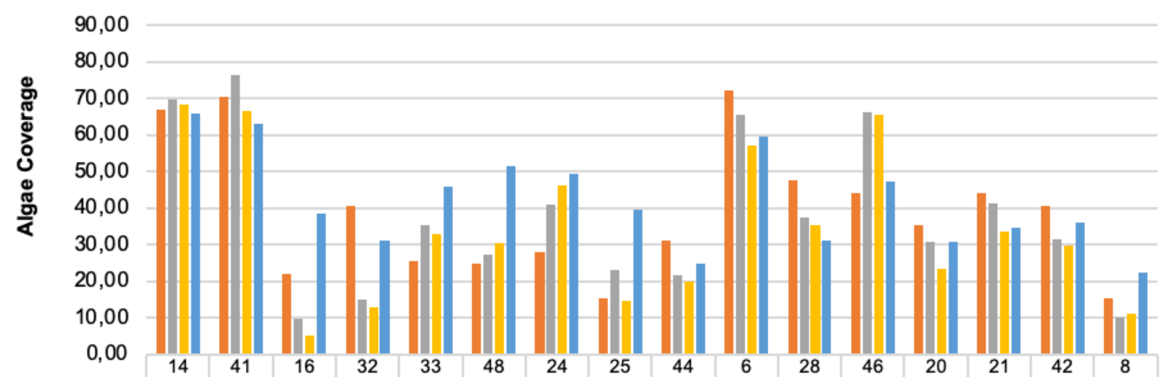


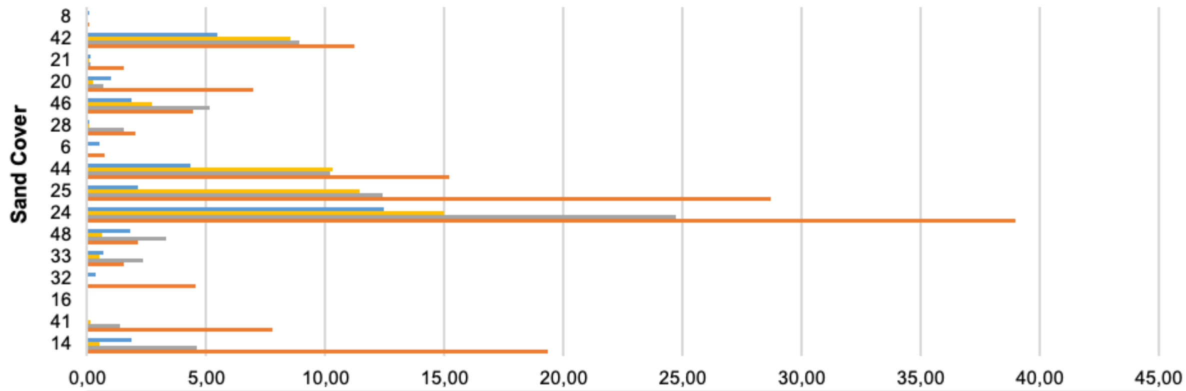
	14	41	16	32	33	48	24	25	44	6	28	46	20	21	42	8
2021	67,13	70,40	21,87	40,67	25,47	24,87	28,07	15,33	31,13	72,27	47,55	44,27	35,27	44,13	40,63	15,47
2022	69,87	76,47	9,73	15,13	35,33	27,33	41,13	23,09	21,60	65,53	37,53	66,27	30,67	41,27	31,60	10,27
2023	68,27	66,60	5,33	12,87	33,07	30,33	46,27	14,73	19,93	57,27	35,47	65,40	23,47	33,60	29,93	11,07
2024	66,00	63,13	38,53	31,13	46,00	51,67	49,56	39,60	24,80	59,53	31,13	47,47	30,93	34,73	35,93	22,33

Fig 4. Graph of percentage of algae cover at various observation stations in the Pieh Island Conservation Area from 2021 to 2024

In addition, several stations exhibit fluctuating patterns that reflect the complex dynamics of the coral reef ecosystem. For example, PIEC 32 experienced a significant decline in algal coverage from 40.67% in 2021 to 12.87% in 2023, before rising again to 31.13% in 2024. PIEC 48 and PIEC 24 showed similar trends, with substantial increases in 2024 following periods of fluctuation in previous years. Meanwhile, some stations, such as PIEC 6, demonstrated a steady downward trend, with algal coverage decreasing from 72.27% in 2021 to 59.53% in 2024.

Sand coverage

Based on sand coverage data from 16 PIEC stations during the 2021–2024 period, there is a noticeable variation among the locations (Fig. 5). Station PIEC 24 consistently has the highest sand coverage value compared to other stations, although it continues to decline from 39.00% (2021) to 12.47% (2024). A similar decrease is also evident at Station 25, which was reduced from 28.73% (2021) to only 2.13% (2024). Several other stations, such as PIEC Stations 44 and 42, show a gradual decreasing pattern. On the other hand, some stations have significantly low sand coverage or even 0% for several consecutive years, such as PIEC Stations 16 and 8, which recorded the highest sand coverage of 0.07% in both 2021 and 2024. Meanwhile, stations like Station 33 (1.53% in 2021 to 0.67% in 2024) and Station 48 (2.13% in 2021 to 1.80% in 2024) experienced less dramatic fluctuations but still showed a tendency to rise and fall year by year.



	14	41	16	32	33	48	24	25	44	6	28	46	20	21	42	8
2024	1,87	0,00	0,00	0,33	0,67	1,80	12,47	2,13	4,33	0,53	0,07	1,87	1,00	0,13	5,47	0,07
2023	0,53	0,13	0,00	0,00	0,53	0,60	15,00	11,47	10,33	0,00	0,07	2,73	0,27	0,07	8,53	0,00
2022	4,60	1,40	0,00	0,00	2,33	3,33	24,73	12,43	10,20	0,00	1,53	5,13	0,67	0,13	8,93	0,00
2021	19,33	7,80	0,00	4,53	1,53	2,13	39,00	28,73	15,20	0,73	2,04	4,47	7,00	1,53	11,21	0,07

Station (PIEC)

Fig. 5. Graph of sand cover percentage at various observation stations in the Pieh Island Conservation Area from 2021 to 2024

Coral mortality index

The Coral Mortality Index (IM) is an important indicator for assessing the mortality rate of corals within a coral reef ecosystem. This index reflects the proportion of dead corals to the total coral cover, making it useful for identifying the level of damage to the ecosystem caused by both natural and anthropogenic factors **(Najmi *et al.*, 2021)**. An IM value close to 0 indicates a low mortality rate, while a value approaching 1 signifies a very high mortality rate, which may suggest significant environmental disturbances such as coral bleaching, water pollution, or other anthropogenic pressures **(Lalang *et al.*, 2022)**.

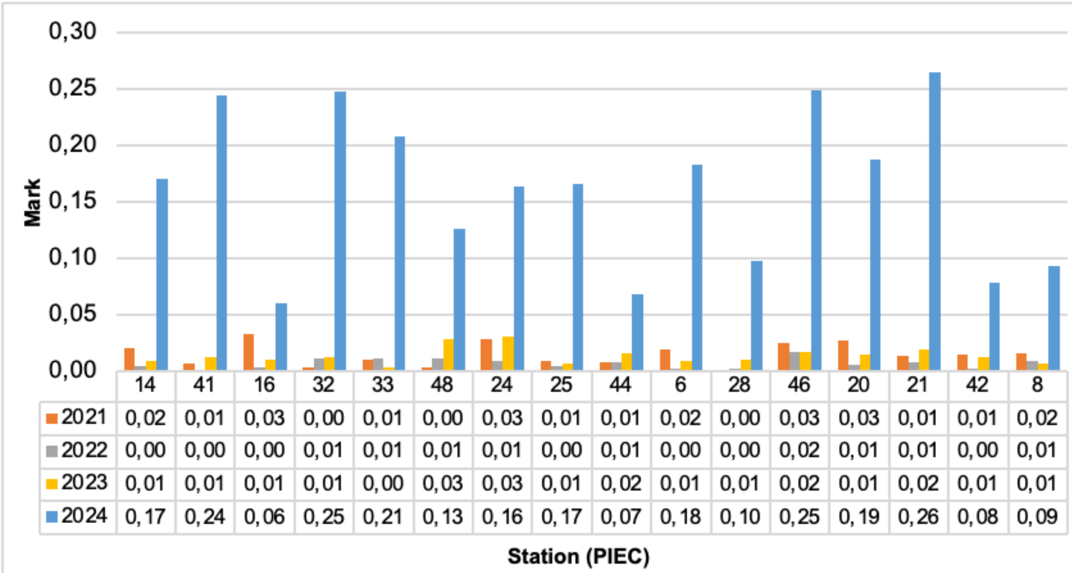
The analysis of the Coral Mortality Index across 16 PIEC stations from 2021 to 2024 reveals significant fluctuations at several locations (see Table 5). Overall, from 2021 to 2023, the mortality index remained relatively low, with most stations recording values ≤ 0.03. However, in 2024, a noticeable increase was observed at several stations—particularly PIEC 41, 32, 33, 46, and 21—where values rose to between 0.21 and 0.26. PIEC 41 recorded the highest index in 2024 (0.24), followed closely by PIEC 42 (0.26) and PIEC 32 (0.25). These elevated values indicate a higher rate of coral mortality compared to previous years. The rising mortality index suggests increasing ecological stress on the coral reef ecosystem, likely driven by a combination of environmental factors and human activities **(Mendoza *et al.*, 2023)**.

Table 5. Coral health condition assessment

St. PIEC	**2021**							
	LCC (%)	**Criteria**	**AC (%)**	**Criteria**	**SC (%)**	**Criteria**	**IM**	**Criteria**
14	6,40	Bad	67,13	Curently	19,33	Very Good	0,02	Low
41	9,20	Bad	70,40	Curently	7,80	Very Good	0,01	Low
16	71,27	Good	21,87	Very Good	0,00	Very Good	0,03	Low
32	37,47	Curently	40,67	Good	4,53	Very Good	0,00	Low
33	66,13	Good	25,47	Good	1,53	Very Good	0,01	Low
48	57,13	Good	24,87	Very Good	2,13	Very Good	0,00	Low
24	20,67	Bad	28,07	Good	39,00	Good	0,03	Low
25	52,13	Good	15,33	Very Good	28,73	Good	0,01	Low
44	25,73	Sedang	31,13	Good	15,20	Very Good	0,01	Low
6	17,20	Bad	72,27	Curently	0,73	Very Good	0,02	Low
28	40,27	Curently	47,55	Good	2,04	Very Good	0,00	Low
46	7,80	Bad	44,27	Good	4,47	Very Good	0,03	Low
20	46,00	Curently	35,27	Good	7,00	Very Good	0,03	Low
21	48,80	Curently	44,13	Good	1,53	Very Good	0,01	Low
42	27,62	Curently	40,63	Good	11,21	Very Good	0,01	Low
8	80,80	Very Good	15,47	Very Good	0,07	Very Good	0,02	Low
St. PIEC	**2022**							
	LCC (%)	**Criteria**	**AC (%)**	**Criteria**	**SC (%)**	**Criteria**	**IM**	**Criteria**
14	17,27	Bad	69,87	Curently	4,60	Very Good	0,00	Low
41	20,67	Bad	76,47	Bad	1,40	Very Good	0,00	Low
16	88,80	Very Good	9,73	Very Good	0,00	Very Good	0,00	Low
32	79,20	Very Good	15,13	Very Good	0,00	Very Good	0,01	Low
33	45,80	Curently	35,33	Good	2,33	Very Good	0,01	Low
48	55,33	Good	27,33	Good	3,33	Very Good	0,01	Low
24	22,93	Bad	41,13	Good	24,73	Very Good	0,01	Low
25	60,81	Good	23,09	Very Good	12,43	Very Good	0,00	Low
44	34,47	Curently	21,60	Very Good	10,20	Very Good	0,01	Low
6	26,73	Curently	65,53	Curently	0,00	Very Good	0,00	Low
28	55,00	Good	37,53	Good	1,53	Very Good	0,00	Low
46	11,33	Bad	66,27	Curently	5,13	Very Good	0,02	Low
20	56,60	Good	30,67	Good	0,67	Very Good	0,01	Low
21	53,67	Good	41,27	Good	0,13	Very Good	0,01	Low
42	40,73	Curently	31,60	Good	8,93	Very Good	0,00	Low
8	85,87	Very Good	10,27	Very Good	0,00	Very Good	0,01	Low
St. PIEC	**2023**							
	LCC (%)	**Criteria**	**AC (%)**	**Criteria**	**SC (%)**	**Criteria**	**IM**	**Criteria**
14	21,07	Bad	68,27	Curently	0,53	Very Good	0,01	Low
41	27,27	Curently	66,60	Curently	0,13	Very Good	0,01	Low
16	90,27	Very Good	5,33	Very Good	0,00	Very Good	0,01	Low
32	82,73	Very Good	12,87	Very Good	0,00	Very Good	0,01	Low

33	52,60	Good	33,07	Good	0,53	Very Good	0,00	Low
48	56,73	Good	30,33	Good	0,60	Very Good	0,03	Low
24	28,07	Curently	46,27	Good	15,00	Very Good	0,03	Low
25	69,87	Good	14,73	Very Good	11,47	Very Good	0,01	Low
44	34,53	Curently	19,93	Very Good	10,33	Very Good	0,02	Low
6	31,47	Curently	57,27	Curently	0,00	Very Good	0,01	Low
28	59,67	Good	35,47	Good	0,07	Very Good	0,01	Low
46	22,73	Bad	65,40	Curently	2,73	Very Good	0,02	Low
20	66,27	Good	23,47	Very Good	0,27	Very Good	0,01	Low
21	59,67	Good	33,60	Good	0,07	Very Good	0,02	Low
42	46,93	Curently	29,93	Good	8,53	Very Good	0,01	Low
8	83,07	Very Good	11,07	Very Good	0,00	Very Good	0,01	Low
St. PIEC	**2024**							
	LCC (%)	**Criteria**	**AC (%)**	**Criteria**	**SC (%)**	**Criteria**	**IM**	**Criteria**
14	16,53	Bad	66,00	Curently	1,87	Very Good	0,17	Low
41	26,60	Curently	63,13	Curently	0,00	Very Good	0,24	Low
16	42,67	Curently	38,53	Good	0,00	Very Good	0,06	Low
32	47,27	Curently	31,13	Good	0,33	Very Good	0,25	Low
33	32,27	Curently	46,00	Good	0,67	Very Good	0,21	Low
48	28,60	Curently	51,67	Curently	1,80	Very Good	0,13	Low
24	23,06	Bad	49,56	Good	12,47	Very Good	0,16	Low
25	44,93	Curently	39,60	Good	2,13	Very Good	0,17	Low
44	32,67	Curently	24,80	Very Good	4,33	Very Good	0,07	Low
6	23,53	Bad	59,53	Curently	0,53	Very Good	0,18	Low
28	58,87	Good	31,13	Good	0,07	Very Good	0,10	Low
46	25,20	Curently	47,47	Good	1,87	Very Good	0,25	Low
20	47,20	Curently	30,93	Good	1,00	Very Good	0,19	Low
21	44,60	Curently	34,73	Good	0,13	Very Good	0,26	Low
42	35,47	Curently	35,93	Good	5,47	Very Good	0,08	Low
8	61,53	Good	22,33	Very Good	0,07	Very Good	0,09	Low

Although several stations experienced a significant increase in coral mortality, there were also stations that maintained consistently low mortality indices throughout the study period. For instance, PIEC 16 and PIEC 8 recorded mortality indices of ≤0.09 in 2024. This suggests that locations with more stable environmental conditions and lower anthropogenic pressure exhibit greater resilience to environmental changes **(Idris *et al.*, 2020)** (Fig. 6).



	14	41	16	32	33	48	24	25	44	6	28	46	20	21	42	8
2021	0,02	0,01	0,03	0,00	0,01	0,00	0,03	0,01	0,01	0,02	0,00	0,03	0,03	0,01	0,01	0,02
2022	0,00	0,00	0,00	0,01	0,01	0,01	0,01	0,00	0,01	0,00	0,00	0,02	0,01	0,01	0,00	0,01
2023	0,01	0,01	0,01	0,01	0,00	0,03	0,03	0,01	0,02	0,01	0,01	0,02	0,01	0,02	0,01	0,01
2024	0,17	0,24	0,06	0,25	0,21	0,13	0,16	0,17	0,07	0,18	0,10	0,25	0,19	0,26	0,08	0,09

Fig. 6. Mortality index graph at various observation stations in the Pieh Island Conservation Area from 2021 to 2024

Coral reef condition assessment

Based on the assessment of coral reef conditions at various observation stations across the Pieh Island Conservation Area, there were significant variations in reef conditions from 2021 to 2024. The assessment was conducted using four key parameters: Live Coral Cover (LCC), Algae Cover (AC), Sand Cover (SC), and the Index of Mortality (IM). These parameters collectively provide a comprehensive picture of reef ecosystem health and the environmental pressures affecting its sustainability. The conservation area is divided into several management zones: rehabilitation, core, tourism, and utilisation zones.

The rehabilitation zone includes PIEC 14 and PIEC 41 on Toran Island. The core zone comprises PIEC 16 (Toran Island), PIEC 32 and PIEC 33 (Air Island), PIEC 24 and PIEC 25 (Pieh Island), PIEC 06 and PIEC 28 (Bando Island), and PIEC 20 and PIEC 21 (Pandan Island). The tourism zone is represented by PIEC 48 (Pieh Island), while the utilisation zone includes PIEC 44 (Pieh Island), PIEC 46 (Bando Island), and PIEC 42 and PIEC 08 (Pandan Island). Overall, trends in coral reef ecosystem conditions varied across the different zones throughout 2021–2024.

In the rehabilitation zone (PIEC 14 and PIEC 41, Toran Island), live coral cover (LCC) was generally low and categorised as Bad to Moderate throughout 2021–2024. In 2021 and 2022, coral cover was classified as Bad but showed gradual improvement—from 6.40 and 9.20% (2021) to 17.27 and 20.67% (2022). This upward trend continued in 2023, with coral cover reaching 21.07 and 27.27%, with one station entering the Moderate category. However, in 2024, a slight decline was observed at PIEC 14 (16.53%, Bad category), while PIEC 41 remained in the Moderate category (26.60%). Algae cover fluctuated within the Moderate category, ranging between 63.13 and 76.47%, whereas sand cover showed a significant decrease from 19.33 and 7.80% in 2021 to just 0.53 and 0.13% in 2023, before increasing again to 1.87% in 2024. The Mortality Index (IM) in this zone remained relatively low (≤0.24) until a notable increase was observed in 2024 (0.17 and 0.24). Despite continued algal dominance and fluctuations in 2024, these trends suggest that rehabilitation efforts have positively impacted ecosystem recovery. However, further measures are needed to achieve "Good" or "Very Good" reef conditions, as rehabilitation zones are specifically designated for the protection and recovery of degraded ecosystems **(Abdurrahim *et al.*, 2020)**. More effective rehabilitation strategies are necessary to accelerate coral reef restoration.

The core zone is a part of the conservation area that is relatively pristine and minimally disturbed by human activities, playing a vital role in maintaining biodiversity **(Abdurrahim *et al.*, 2020)**. In the core zone (PIEC 16, PIEC 32, PIEC 33, PIEC 24, PIEC 25, PIEC 06, PIEC 28, PIEC 20, and PIEC 21), there has been a trend of increasing coral cover from 2021 to 2023, followed by a significant decline in 2024, which is accompanied by an increase in algal cover in several locations. This increase in algae is not always attributed to anthropogenic disturbances but can also be influenced by environmental factors such as wave activity, water clarity, tides, as well as increased nutrient and sediment input from land. These conditions may hinder coral regeneration and trigger a shift in ecosystems from coral dominance to algal dominance, ultimately reducing the ecological functions of coral reefs **(Cannon *et al.*, 2023*;* Fabricius *et al.*, 2023)**. PIEC 06 has the lowest coral cover in the zone, remaining within the Moderate category from 2021 to 2024. Additionally, sand cover experienced a drastic decline from 2021 to 2023, before increasing again in 2024. Meanwhile, the Mortality Index (IM) remained in the Low category throughout 2021–2024, although it saw a slight increase in 2024, reflecting intensifying environmental pressure. Although still categorized as Low, this increase indicates the potential rise in coral mortality due to ongoing environmental stressors, which—if not well-managed—could further accelerate coral reef degradation **(Hughes *et al.*, 2017)**.

In the tourism zone (PIEC 48), the coral reef ecosystem has experienced significant fluctuations from 2021 to 2024. The percentage of coral cover remained stable within the Good category from 2021 to 2023 but drastically declined to a Moderate level in 2024. This suggests environmental pressures or increased tourist activities that may be disrupting coral growth. Algal cover gradually increased from 24.87% in 2021 to 51.67% in 2024, moving from the Very Good to Moderate category. This reflects the growing competitive advantage of algae over corals, as algae begin to dominate substrate previously occupied by coral. Sand cover fluctuated within the Very Good range throughout 2021–2024. The Index of Mortality (IM) remained Low (≤ 0.13) during the observation period, although it increased in 2024, potentially indicating rising environmental stress. Overall, this trend suggests that although the tourism zone maintained Good coral conditions until 2023, increased environmental pressures in 2024 demand management interventions to sustain coral reef health.

The utilisation zone (PIEC 44, PIEC 46, PIEC 42, and PIEC 08) showed variations in coral reef ecosystem conditions from 2021 to 2024. This zone supports marine tourism activities such as swimming, snorkeling, diving, fishing, surfing, and other water sports like jet skiing, banana boat rides, and underwater glass boat tours **(Abdurrahim *et al.*, 2020)**. It is also utilized for fishing, aquaculture, aquatic nature tourism, research, and education **(Bahri, 2019)**. Coral cover increased at several stations—for example, PIEC 46 rose from 7.80% (Bad, 2021) to 25.20% (Moderate, 2024). Conversely, PIEC 08 experienced a significant decline from 85.87% (Very Good, 2022) to 61.53% (Good, 2024). Algal cover showed a contrasting trend to coral cover, reflecting the competition between corals and algae for substrate space. This change was also accompanied by a gradual decrease in sand cover, which remained in the Very Good category throughout the period, indicating a shift in substrate dynamics. The Mortality Index (IM) remained Low at all stations, although it rose to 0.25 at PIEC 46, indicating increasing environmental pressure.

DISCUSSION

Water quality

Some PIEC stations recorded salinity levels exceeding the optimal range (33–34 ppt) in both 2021 and 2024, indicating significant spatial and temporal variability in this parameter. Notably, station PIEC 25 showed a drastic decrease in salinity, dropping from 43ppt in 2021 to 25ppt in 2022. While several studies have shown that coral reefs can survive within salinity ranges of 25– 40ppt **(Rina *et al*., 2020; Isdianto *et al.*, 2024)**, prolonged exposure to extreme levels—especially at the upper limit—can induce physiological stress, impair osmoregulation, disrupt zooxanthellae symbiosis, and increase the risk of coral bleaching.

These fluctuations are likely driven by water hydrodynamics, seasonal rainfall variability, and freshwater intrusion, which alter the salinity balance across the monitored area. Over the four-year study period, a general decline in water quality was observed across the 16 research stations, particularly reflected in decreased dissolved oxygen (DO) levels and elevated salinity. These changes pose a serious threat to coral reef survival and the broader marine biodiversity that depends on stable water parameters.

Coral cover trends

Coral cover varied substantially between 2021 and 2024, influenced by both natural disturbances and anthropogenic stressors **(Farma *et al.*, 2024)**. Global-scale phenomena such as climate change, ocean warming, and acidification have intensified the occurrence of coral bleaching, weakened coral immune systems, and impaired calcification processes, leading to the gradual degradation of coral ecosystems.

Additionally, land-based pollution—particularly sediment runoff—is among the most damaging local threats to coral reefs **(Tuttle & Donahue, 2022)**. Sediments often carry toxic compounds, pathogens, and excess nutrients, leading to increased coral mortality, inhibited growth, shifts in species composition, and disruption of reef-associated fish communities.

Algal cover dynamics

Algal cover fluctuations during the study period were closely tied to environmental and ecological pressures. Eutrophication, stemming from increased nutrient input (e.g., agricultural runoff, coastal development), fosters algal blooms and can shift the ecosystem from coral dominance to algal dominance, especially when herbivorous fish populations decline **(Idris *et al.*, 2020; Isdianto *et al.*, 2023)**.

Herbivorous fish are essential for controlling macroalgae, maintaining coral health, and preventing competitive exclusion of corals by fast-growing algae **(Sheppard *et al*., 2023; Isdianto *et al.*, 2024)**. Sea temperature fluctuations and biological interactions with macroalgae and coral species also influence algal growth patterns. Observed variations in algal coverage across stations underscore the ecosystem's response to local disturbances, impacting the overall sustainability of coral reef habitats.

Sand cover and sedimentation

Stations such as PIEC 24 and PIEC 25 initially experienced high sedimentation, which gradually declined over time as substrate conditions stabilized and sediment input reduced. According to **Fukunaga *et al.* (2023)**, sand cover is inversely related to hard substrate availability, as rigid substrate area is typically calculated by subtracting sand coverage from 100%. Therefore, increases in sand coverage effectively reduce available space for coral colonization and reef fish habitat.

Sand represents an unstable substrate, impeding the settlement of coral planulae, which require firm surfaces for successful recruitment **(Polapa & Suharto, 2023)**. Wave action and currents further complicate attachment by continually displacing sand particles, reducing the chances for larval survival and growth **(Luthfi & Anugrah, 2017)**.

The trends in sand cover observed across the monitoring stations reflect the interplay of hydrodynamic forces, substrate stability, and human-induced changes, all of which influence the long-term health and regeneration potential of coral reefs in the area.

CONCLUSION

This study offers a comprehensive spatio-temporal assessment of coral reef health within the Pieh Island National Conservation Area from 2021 to 2024, incorporating both biological and environmental indicators across 16 monitoring stations located in core, rehabilitation, tourism, and utilization zones. The results reveal complex and dynamic patterns in coral reef condition, shaped by both natural variability and anthropogenic pressures. Live Coral Cover (LCC) generally showed an upward trend from 2021 to 2023, particularly in core zones such as PIEC 16 and PIEC 8, which reached peak values of 90.27 and 83.07%, respectively. These findings reflect the effectiveness of conservation measures and favorable environmental conditions during that period. However, a marked decline in coral cover occurred in 2024, most notably at PIEC 16, where coverage fell to 42.67%. This drop is likely associated with thermal stress (sea surface temperatures exceeding 31.7°C), hypoxia (DO < 5 mg/L at multiple stations), and elevated salinity levels (> 37 ppt). The Coral Mortality Index (IM) remained relatively low (< 0.03) between 2021 and 2023, indicating stable ecological conditions. Yet, IM values rose sharply in 2024 at several stations, including PIEC 41 (0.24), PIEC 32 (0.25), and PIEC 21 (0.26), pointing to acute stress events, possibly caused by sedimentation and low oxygen availability. Algal cover was consistently high in rehabilitation and utilization zones, with values exceeding 60% at stations like PIEC 14 and PIEC 41. This suggests nutrient enrichment, reduced herbivory, and ecosystem imbalance. Concurrently, sand cover declined over time, implying increased substrate exposure for colonization but also greater sediment movement, potentially affecting coral recruitment. Rehabilitation zones exhibited gradual recovery, as seen in PIEC 14, where coral cover increased from 6.4% in 2021 to 21.07% in 2023—though still within the “Bad” to “Moderate” categories. Core zones, which initially showed the healthiest reef conditions, experienced the most significant setbacks in 2024. Meanwhile, tourism and utilization zones showed high ecological variability, with coral loss and algal blooms pointing to pressures from recreational overuse and resource extraction. In conclusion, the sharp deterioration in coral health observed in 2024, following earlier improvements, underscores the vulnerability of coral reef ecosystems to compounded stressors. The findings highlight the urgent need for adaptive, zone-specific conservation strategies, including strengthened water quality monitoring, stricter regulation enforcement, and ecosystem-based rehabilitation. Achieving long-term ecological resilience will require enhanced collaborative governance involving local communities, marine conservation authorities, and stakeholders, to ensure the sustainable management of the Pieh Island coral reef ecosystems.

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