INTERNATIONAL JOURNAL OF CONSERVATION SCIENCE

ISSN: 2067-533X Volume 15, Issue 4, 2024: 1947-1958 www.ijcs.ro

DOI: 10.36868/IJCS.2024.04.24

THE ECOLOGICAL HEALTH OF CORAL REEFS IN THE WATERS OF ENGGANO ISLAND, THE OUTERMOST ISLAND IN THE EASTERN INDIAN OCEAN

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Abstract

Enggano waters are located in the outer waters of the eastern Indian Ocean which is thought to have a cluster of coral reefs that are important for marine ecosystems. Coral reef ecosystems have important benefits for marine and human life. The existence of coral reefs in the outer waters needs to be monitored so as not to exploit its natural resources. This study aims to monitor coral reef ecosystems through biological and physical-chemical approaches. Coral reef data collection using the Underwater Photo Transect (UPT) method was supported by 50 m transect lines and quadrant transects measuring 58 x 44cm. Underwater data recording used an Olympus Tough TG-6 digital camera. Physical-chemical data were taken in situ using portable devices and ex situ data in the form of nitrate and phosphate were analyzed in the laboratory. The results showed that the percentage of live coral cover ranged from 8.83% - 71.11%. Based on the results, 7 forms of coral reef growth were found and consisted of 14 coral reef genus. In general, the health level of coral reefs in Enggano Waters was in the medium category. Coral reef density ranged from 1.67 - 5.52colony/m^2, diversity index was moderate, evenness index was high and dominance index was low. In general, physical-chemical parameters were at optimal values for coral reef life except salinity which was quite low. Salinity ranging from 14 - 19‰ was a parameter that was feared to be able to significantly affect the life, sustainability and balance of the coral reef ecosystem.

***Keywords**: Biodiversity; Coral reefs; Ecological health; Enggano waters*

Introduction

Coral reefs are one of the marine ecosystems for many marine biodiversity habitats located in tropical and sub-tropical regions [1]. They provide habitat for many marine organisms such as reef fish, sea snails, bivalves, crabs, sea cucumbers, squid and many more [2-4].

Coral reefs are also recognized as ecosystems with the greatest value of ecosystem services to humans [5]. These benefits can be categorized as direct benefits and indirect benefits. The needs of coastal communities basically depend more on the benefits provided by coral reef ecosystems [3, 6]. The strength of coral reef benefits is very high for community food supply,

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provision of tourist areas, shoreline protection and utilization for marine bioprospecting products [7-9].

Complex ecosystems such as coral reefs require a good ecological balance [10]. However, sometimes many local activities can trigger ecological interactions, including predation or competition between organisms, the pressure of anthropogenic activities such as pollution, fisheries, agriculture and tourism [11, 12].

Several coral reef health evaluation techniques can currently be used, depending on suitability to the site and its circumstances. In general, measurements of coral reef condition can be made through biological and physical-chemical approaches [13]. The biological survey approach will rely on simple means of measuring coral reef quality and quantity using transect techniques, while the physical-chemical survey approach will reveal the condition of more complex coral reef habitat environmental parameters with specialized measuring equipment [9, 14].

The Indian Ocean is the third major ocean in the world after the Pacific Ocean and the Atlantic Ocean. The Indian Ocean is one of the oceans that store and maintain the world's megabiodiversity [15]. Geographically, it is an international ocean that borders directly with many administrative waters of various countries that have different water characteristics [16]. One of the outermost water areas is the waters of Enggano Island, which is administratively included in Indonesian waters.

Enggano Island is one of the outermost small islands of the Indian Ocean with an area of ±400 and ±100km^2 from Sumatra mainland. This island is located in the west of Sumatra Island which has clearer waters and a minimum of suspended sediments so it is thought to store a cluster of coral reefs [17]. Reports on habitat conditions in these waters are quite minimal, especially with regard to coral reef habitats. Whereas reports on coral reef habitats, especially those in outer waters, are very important in preservation and conservation efforts [18, 19].

Strategies for monitoring marine bioindicators through coral reef health monitoring are critical [20]. They are able to provide early warning signs for the health and sustainability of the ecological components that live in them because they are ecological components that are very sensitive to extreme environmental changes [21, 22]. As marine bioindicators, coral reefs can be identified by their health based on the percentage of coral cover and the diversity of coral species living on them [23, 24].

The main objective of this research is to assess the health of coral reefs in Enggano waters through biological approaches and physical-chemical approaches. From the study will be evaluated and analyzed whether there is a special relationship between variables that affect each other because each water area in the world tends to have a distinctive character.

Experimental part

Study Site

Two coral reef sites were selected in the north and south of Enggano Island (Fig. 1). Location N (North) was in Banjarsari village and location S (South) was in Kahyapu village which was included in the administrative area of Bengkulu province, Indonesia. The north location consisted of three sampling stations and the south location consisted of two sampling stations. The north site was located in the bay area in the northern part of Enggano, while the south site was located on a cluster of small island reefs (Dua Island).

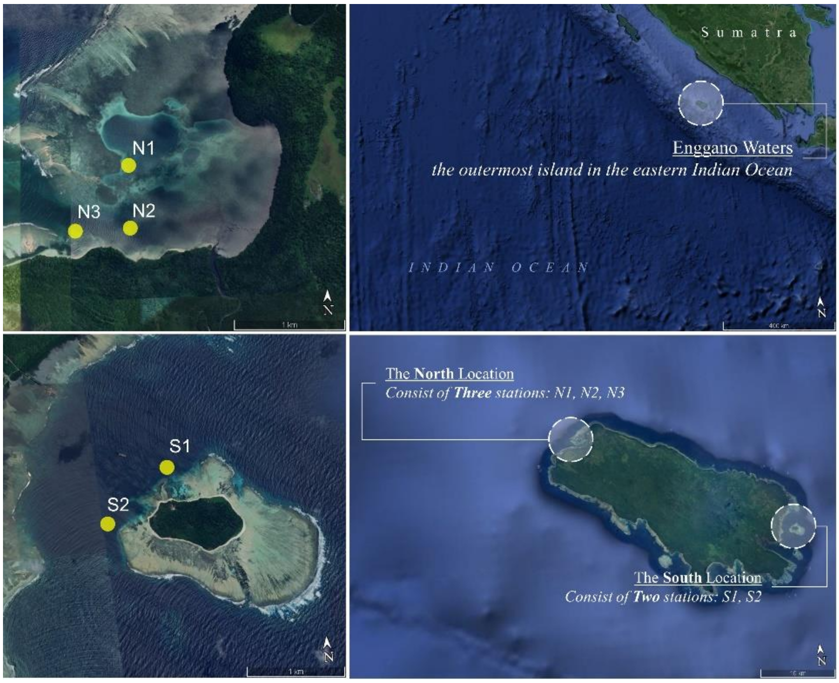

Fig. 1. Map of sampling location

Methods

Ecological survey of coral reef community structure

Coral reef data collection using the Underwater Photo Transect (UPT) method [25, 26]. The length of the transect line used was 50m with quadrant transects measuring 58 x 44cm. Underwater photography was taken using an Olympus Tough TG-6 underwater digital camera. Coral reef data collection at each station was carried out at two depths, namely 3 and 6m depth.

Photographs were taken every 1.0m interval with a zig-zag pattern. A collection of photos was analyzed using the CPCe (Coral Point Count with Excel Extension) software [27, 28]. The analysis results will present the percentage of five components namely C (live coral), ALG (algae), OT (other invertebrates), DC (dead coral) and (SR) sand, silt and rock.

Data collection of Environmental physic-chemical parameters

Data collection of physical-chemical parameters of the environment was carried out in situ and ex situ. In situ parameters include temperature, salinity, pH, dissolved oxygen, water brightness, current speed. These parameters were measured using portable devices, namely multiparameter (temperature and dissolved oxygen), hand refractometer (salinity), pH meter (pH), secchi disk (water brightness), flow meter (water current). Meanwhile, ex situ parameters were measured in the laboratory in the form of water nutrient levels including nitrate and phosphate [29-31].

Data analysis

Coral reef cover data obtained from underwater photos that have been processed by CPCe, analyzed using the formula [32]. Then, coral reef biodiversity data were analyzed using biodiversity analysis which includes coral density, diversity index (H'), evenness index (E) and dominance index (C) [33-35].

Based on the data that has been obtained, namely coral cover data, coral reef biodiversity data and environmental physical-chemical parameter data. This component analysis was carried out to determine the relationship group between these variables to revealed the characteristics that occured in Enggano waters. The analysis used was Principal Component Analysis (PCA) which was analyzed with XLSTAT 2023 software [36-38].

Results and discussion

Coral reef community structure

Based on the results of the analysis of coral reef cover, there are three categories that are percentageed, namely life coral, dead coral and others. The others include macro algae, rubble, sand, silt, rock and other fauna. The percentage of each component was presented in Table 1.

Table 1. The percentage of coral reef cover in Enggano Waters

Category	Code	Percentage of coral reef cover at each station (%)										Ave
		N1		N2		N3		S1		S2		
		D3	D6	D3	D6	D3	D6	D3	D6	D3	D6	
Life Coral												
Branching Acropora	ACB	2.56	0	13.44	6.89	1.99	0.42	0	3.33	9.37	17.10	5.51
Digitate Acropora	ACD	0	0	0.17	0.67	0	0	0.20	0	0.26	0	0.13
Encrusting Acropora	ACE	0	0	0	0	2.44	4	0	0	0.32	0	0.68
Submassive Acropora	ACS	22.64	0	0	0	2.31	3.92	0.85	2.59	2.76	5.49	4.06
Tabulate Acropora	ACT	0.39	0	0	0	1.41	0	0	0	0	0	0.18
Branching Coral	CB	17.63	0	1.44	2.67	0.90	0.08	11.63	5.19	0.96	4.44	4.50
Encrusting Coral	CE	0	0	0.44	0	0	0	0.46	0	0	0	0.09
Foliose Coral	CF	0	0	47.61	37.58	0	0	0	0	0	0.56	8.57
Heliopora Coral	CHL	0.33	0	6.28	5.56	0	0	20.07	0.07	0.26	0	3.26
Massive Coral	CM	1.06	0	1.61	1.83	13.72	0.42	0.46	0.15	5.91	1.91	2.71
Millepora Coral	CME	2.73	0	0	6.89	0	0	0.13	1.48	11.10	6.42	2.88
Mushroom Coral	CMR	0	0	0.11	0	0	0	0	0	0	0	0.01
Soft Coral	SC	0	0	0	1.28	0	0	0	0	0	0	0.13
Total		47.33	0.00	71.11	63.37	22.76	8.83	33.79	12.81	30.94	35.93	32.69
Dead Coral												
Recently Dead Coral	DC	3.34	0	2.06	0.44	5.38	2.92	0.52	0	3.72	0	1.84
Dead Coral with algae	DCA	0	0	3.17	4.95	0	0	7.84	13.26	0	2.28	3.15
Total		3.34	0.00	5.23	5.39	5.38	2.92	8.36	13.26	3.72	2.28	4.99
Others												
Macro Algae	MA	0	0	2.39	3.17	0	0	0	0.22	0	0,12	0.64
Rubble	R	28.14	0	6.33	1.78	70.58	86.25	9.61	50.81	34.79	11.98	30.03
Sand	S	3	0	0	0.67	0	0	45.42	1.63	28.82	0	7.95
Silt	SI	18.19	100	14.39	24.96	1.03	2	0.59	20.74	0.71	49.32	23.19
Other (Fauna)	OT	0	0	0	0	0.26	0	0	0	0	0	0.026
Rock	RK	0	0	0.56	0.67	0	0	2.22	0.52	1.03	0.37	0.54
Total		49.33	100	23.67	31.25	71.87	88.25	57.84	73.92	65.35	61.67	62.31

The live coral component at the Enggano Waters location was found in seven forms of reef growth, namely Acropora Branching (ACB), 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), Soft Coral (SC). Based on Table 1, the percentage of live corals at station N2 at a depth of 3 and 6m was in the good category (71.11 and 63.37%). Meanwhile, at station N1 at a depth of 6m no live corals were found, but only consisted of silt type sediments. In general, the cover of live coral reefs in these waters was relatively in the medium category. In these Enggano waters, the percentage of dead coral cover was relatively very low, overall ranging from 2.28% - 13.36%

Based on Table 1, Foliose Coral was the growth form that had the highest percentage with 8.57%. At station N2, the type of Foliose Coral was found at a depth of 3m with a value of 47.61%, while at a depth of 6m the amount was 37.58%, at stations N1, N3 and S1, there were no findings of the Foliose Coral growth form. However, at station S2, the type of Foliose Coral was detected at a depth of 6m as much as 0.56%, while at a depth of 3m, no such type was found

Coral reefs have various types of growth forms. In Enggano waters, the growth form of Foliose Coral is the type that has the highest percentage of cover. One guess why this type of reef is found dominant in Enggano waters because of its ability to survive in its habitat. Enggano waters are strongly influenced by the characteristics of the Indian Ocean waters so that it has a tendency with a strong current and high choppy environment. Foliose Coral has been known for its ability to survive in very dynamic water conditions, although in some studies reported the form of Foliose Coral is rarely found and vulnerable to certain environmental conditions [39-41]. It is able to withstand strong current conditions, very bumpy, significant temperature changes and even in locations with high sedimentation [42, 43].

Coral reefs as one of the constituent components of the benthic zone of the waters, there are several other components found, namely macro algae, rubble, sand, silt, rock and others. The presence of this component in a high percentage indicates that the Enggano water location has a coral reef cover that is not too broad. This data indicates that the coral reef ecosystem in Enggano waters really needs to be maintained. This is related to the ecological function of coral reefs which have important benefits for complex aquatic life [9, 21, 44, 45].

Based on the study, Enggano waters have moderate coral reef health in general. However, in some locations coral reef health was found in the damaged category such as at locations N1, N3, S1 and good category at location N2. Several locations scattered in the Indian Ocean region have reported their coral reef health conditions. In the Comoros Archipelago, Western Indian Ocean region, the health of the coral reefs was in medium health condition [46], The Gulf of Mannar waters showed a coral reef health category in a declining condition approaching damage with a live coral cover of 22.69 ± 9.07% [47]. When the health of coral reefs in Enggano waters was compared to some of its closest regional waters, it showed better results. In West Aceh waters, coral reefs were were in poor condition with a coral cover percentage of 17.6% [48]. The same was reported in the waters off Mande, West Sumatra with poor to moderate health conditions [49].

Coral reef health was very important to evaluate for conservation and sustainability considerations. Coral reef health was assessed through four categories: poor, medium, good and very good. Coral reef health levels in Enggano Waters were presented in Table 2.

Based on Table 2, the assessment of coral reef health was determined by the percentage of live coral cover found at the site. The percentage of coral reef cover in Enggano waters ranged from 0 - 71%. Coral reef health in the damaged category was located at the location of N1 at a depth of 6m, N3 at a depth of 3 and 6m and S1 at a depth of 6m. Coral reef health in the medium category was located at location N1 at a depth of 3m, S1 at a depth of 3m and S2 3 and 6m. Then, coral reef health in the good category was found at location N2 at a depth of 3 and 6m.

Table 2. The health category of life coral cover in Enggano Waters

Stations	Coordinate		Depth (m)	Life Coral Cover (%)	Health category	Category Percentage
	Longitude	Latitude				
N1	102.1268	-5.30646	3	47	Medium	
			6	0	Poor	
N2	102.1265	-5.31102	3	71	Good	
			6	63	Good	Poor = 0 - 24.9%,
N3	102.1219	-5.31143	3	23	Poor	Medium = 25-49.9%,
			6	9	Poor	Good = 50-74.9%,
S1	102.3899	-5.43841	3	34	Medium	Very Good = 75-100%
			6	13	Poor	
S2	102.3838	-5.44261	3	31	Medium	
			6	36	Medium	
Average				33	Medium	

Based on Table 3, the identified coral reefs were 14 genus consisting of *Acropora, Anacropora, Montipora, Dendronephthya, Goniastrea, Montastrea, Heliopora, Millepora, Pachyseris, Pavona, Porites, Psammocora, Scolymia* and *Seriatopora*. The highest reef density was at station N2 with a value of 5.52colony/m², consisting of 11 genera with 169 colonies, while the least density was found at station N3 with an abundance value of 1.67colonies/m² with the number of genus found as many as 5 genus and the number of colonies as many as 51 colonies. The density of coral reef genus presented in Table 3 that the most common genus found in Enggano Waters was Montipora with 73 colonies at station N2.

Table 3. The existence of coral genus and colony in the Enggano Waters

No	Family	Genus	Coral Reefs Colony Total										Total
			N1		N2		N3		S1		S2		
			D3	D6	D3	D6	D3	D6	D3	D6	D3	D6	
1	*Acroporidae*	1. *Acropora*	9	-	10	7	3	2	1	4	16	16	68
		2. *Anacropora*	-	-	-	-	-	-	-	1	-	-	1
		3. *Montipora*	-	-	30	43	-	-	-	-	-	-	73
2	*Nephtheidae*	1. *Dendronephthya*	-	-	-	1	-	-	-	-	-	-	1
3	*Faviidae*	1. *Goniastrea*	1	-	2	2	14	2	5	2	16	4	48
		2. *Montastrea*	-	-	-	-	5	3	-	-	1	-	9
4	*Helioporidae*	1. *Heliopora*	1	-	14	5	-	-	40	-	1	-	61
5	*Milleporidae*	1. *Millepora*	4	-	-	-	-	-	-	1	10	13	28
6	*Agariciidae*	1. *Pachyseris*	-	-	-	1	-	-	-	-	-	1	2
		2. *Pavona*	-	-	-	4	-	-	2	-	-	-	6
7	*Poritidae*	1. *Porites*	34	-	-	11	9	7	2	5	7	-	75
8	*Siderastreidae*	1. *Psammocora*	-	-	5	11	-	-	-	-	-	-	16
9	*Mussidae*	1. *Scolymia*	-	-	3	-	-	-	-	-	-	-	3
10	*Pocilloporidae*	1. *Seriatopora*	26	-	12	8	5	1	30	16	2	6	106
Genus Total			6	0	7	10	5	5	6	6	7	5	14
Colony Total per Depth			75	0	76	93	36	15	80	29	53	40	497
Colony Total per Station			75		169		51		109		93		497
Genus Density per Station (colony/m²)			2.45		5.52		1.67		3.56		3.04		-

Coral reef biodiversity index in Enggano Waters which included diversity index (H'), Evenness index (E) and dominance index (C) were presented in Table 4. Diversity index values ranged from 1.25 - 2.23 with the highest value at station N2 and the lowest at station N1. The evenness index value ranges from 0.70 - 0.90 with the highest value at station N2 and the lowest at station N1. The dominance index value ranged from 0.24 - 0.34 with the highest value at station N1 and the lowest at stations N2, N3 and S2.

Table 4. Coral reef biodiversity index value in Enggano waters

Stations	Diversity		Evenness		Dominance	
	H'	Category	E	Category	C	Category
N1	1.25	Medium	0.70	High	0.34	Low
N2	2.23	Medium	0.90	High	0.24	Low
N3	1.28	Medium	0.80	High	0.24	Low
S1	1.47	Medium	0.71	High	0.32	Low
S2	1.71	Medium	0.82	High	0.24	Low

A medium diversity value indicates that the environment is very supportive of the survival of organisms ecologically and is suitable for habitation and has the potential for growth and development [44, 50, 51]. A high evenness value indicates that the coral reef is stable because no species dominates the reef [52]. Dominance values close to zero indicate that the coral reef community structure does not have species that strongly dominate and indicate that the community structure is in a stable condition [53].

Environmental physical-chemical parameters

Measurements of water physical-chemical parameters were taken at each sampling location. The results of parameter measurements in the form of temperature, pH, dissolved oxygen, salinity, current speed, water brightness, nitrate and phosphate were presented in Table 5. Water temperature measured in Enggano waters ranged from 25.6 - 28.5ºC, pH ranged from 6.97 - 8.61, dissolved oxygen ranged from 4.8 - 7.4mg/L, salinity ranged from 14 - 19‰, water current ranged from 0.1 - 0.6m/s, water brightness ranged from 4.84 - 5.32m, nitrate content ranged from 1.569 – 2.186mg/L and phosphate of 0.107mg/L.

Table 5. Environmental physical-chemical parameters in Enggano Waters

Parameters	Stations				
	N1	N2	N3	S1	S2
Temperature (ºC)	27.1	26.7	28.5	25.9	25.6
pH	8.61	7.58	6.97	7.65	7.55
Dissolved oxygen (mg/L)	6.0	4.8	6.9	7.4	7.0
Salinity (‰)	18	17	14	19	16
Water current (m/s)	0.5	0.1	0.1	0.6	0.4
Water brightness (m)	4.84	5.23	5.12	5.32	5.10
Nitrate (mg/L)	1.569	2.186	1.754	2.027	1.594
Phosphate (mg/L)	0.107	0.107	0.107	0.107	0.107

Coral reef ecosystems in Enggano waters show typical correlation values between biological variables and physico-chemical variables. The typical relationship between these variables is illustrated at location N2 which is the location of the highest coral cover in these waters. Based on the results of the analysis, that nitrate concentrations tend to be higher can increase the growth of coral reefs at a depth of 6 m, it is also supported by a slower current speed. Nitrate is known to be an important nutrient for zooxanthellae species that live in coral polyps [54]. However, the salt concentration in Enggano Waters was lower than the ideal condition of salinity of marine waters which was 30 - 35‰. Lower salinity conditions have a negative impact on coral reef survival [50, 55]. Salinity conditions that are not optimal can inhibit the photosynthesis process of Z*ooxanthellae* [56]. If these conditions persist for a long time, it will cause coral bleaching and coral death [57].

Group of variables and relationships

Several groups of variables consisting of coral reef cover and environmental physico-chemical parameters were analyzed to determine the main groups. The results of PCA analysis of these variables are presented in Figure 2.

Based on Figure 2, the eigenvalue obtained was 69.03% by forming 2 main groups namely F1 (41.33%) and F2 (27.69%). Group F1 consisted of variables of live coral cover at a depth of 6 m, density, diversity, evenness and nitrate concentration with observation station at N2. Group F2 consisted of dead coral covers at a depth of 3 and 6m, water current and salinity with observation station at S1.

In general, the condition of coral reef ecosystems in Enggano waters is still quite good based on biological and physical-chemical environmental variables that have been measured. However, there are several measurements that should be the main focus to assess the sustainability of coral reefs in this area. It is known that salinity in this water area is found to tend to be lower in optimal conditions. In the case of station N2, this location is in a bay area that is generally characterized as semi-enclosed. It is suspected that there has been a geomorphological change on the side of the bay that causes low-salinity water not to be mixed into marine waters during tidal conditions.

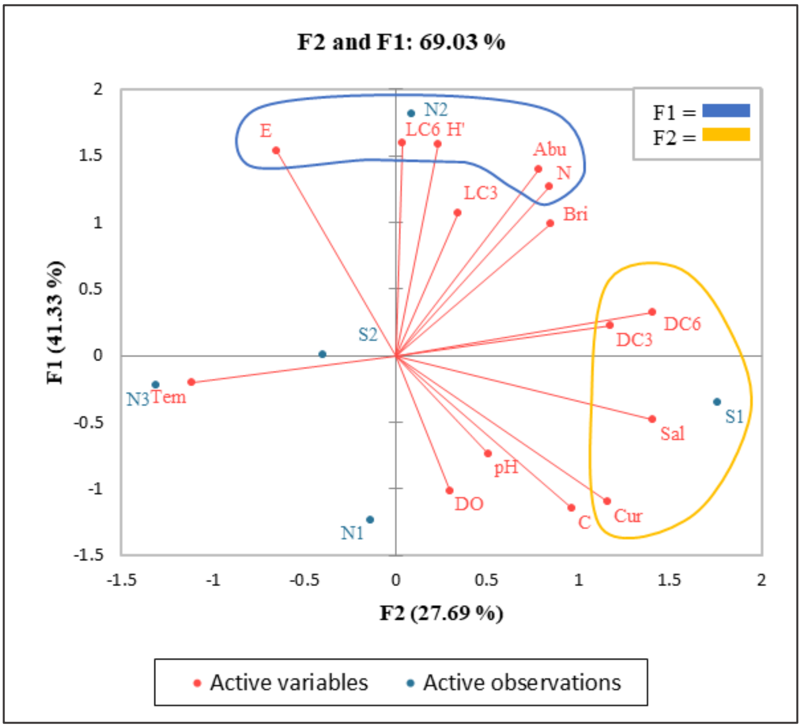

Fig. 2. The correlation of each variable parameters

Based on this, a further study is needed to follow up on the physical-chemical phenomena in Enggano waters comprehensively as an effort to preserve and conserve the coral reef ecosystem in one of the outermost places in the Indian Ocean.

Conclusions

Enggano waters are one of the important waters as the outer waters of the Indian Ocean which has a cluster of coral reefs. The coral reefs found were in fairly good condition. The highest live coral cover had a percentage of 71.11%. Station N2 was the best habitat for coral reefs with good coral reef health category. There were 14 genus of coral found, namely *Acropora, Anacropora, Montipora, Dendronephthya, Goniastrea, Montastrea, Heliopora, Millepora, Pachyseris, Pavona, Porites, Psammocora, Scolymia and Seriatopora*. The genus *Montipora* was the highest found with 73 colonies. Coral density ranged from 1.67 - 5.52colony/m^2. The biodiversity index showed moderate diversity, high evenness and low dominance. The study results showed that the relationship between biological and physical-chemical variables formed two main groups, namely F1 and F2. In the study at site N2, high coral cover at 6 m depth was influenced by nitrate content which tended to be higher, supported by slower current speeds. However, salinity conditions in all sampling sites that tend to be lower than the optimal conditions for coral growth suggest a negative influence on the sustainability of coral reef life in Enggano waters. The results that have been revealed in this study suggest that a comprehensive study on the dynamics of Enggano waters, especially in the bays in the north of Enggano Island.

Acknowledgments

The part of this research was funded by National Research and Innovation Agency of the Republic of Indonesia under the "Riset dan Inovasi untuk Indonesia Maju Gelombang 3" (Grant Number: 12/II.7/HK/2023; Decree Number: 76/IV/KS/05/2023; 0236/UN9.3.1/PL/2023).

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Received: February 15, 2024
Accepted: November 2, 2024