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Linking Benthic Condition, Reef Fish Biomass, and Coral Health Index in a Degraded Reef System of the Sembilan Archipelago

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Abstract

The coral reef ecosystem of the Sembilan Archipelago was evaluated through an integrated ecological survey across eight islands. The study integrated benthic surveys using a point intercept transect method with underwater visual census techniques to evaluate coral reef condition, reef fish diversity, and ecosystem health. Findings suggest a fair ecological state of the islands' reefs, with live coral cover averaging 26.05% and 46 hard coral species recorded. Diversity indices varied among islands, with Shannon-Wiener values ranging from 2.24 to 2.78. Evenness values (0.81-0.93) indicated relatively uniform species distribution, while elevated mortality indices at Pulau Buluh and Pulau Nipis reflected localised degradation. Coral assemblages were dominated by mixed and stress-tolerant species, suggesting ongoing environmental stress. Fifty reef fish taxa were also recorded. Fish biomass was highest at Pulau Payung, while diversity peaked at Pulau Lalang. Variations in fish assemblages were likely driven by habitat quality, reduced coral cover, and anthropogenic pressures. The mean Coral Health Index was 0.39, indicating generally poor reef condition, although several reefs still exhibit moderate coral health. Collectively, the findings indicate deteriorating reef health alongside reduced fish populations, suggesting increasing ecosystem degradation across the archipelago. Given its ecological significance and strategic location, strengthened conservation measures, including designation as a protected area, are recommended to conserve biodiversity, enhance reef resilience, and support long-term ecosystem recovery.

Keywords: Benthic Cover; Fish Biomass; Species Diversity; CHI; Strait of Malacca

Introduction

Coral reefs are widespread in tropical marine waters, from Australia's Great Barrier Reef to the Caribbean, and typically occur in shallow coastal areas with warm, stable temperatures of around 28°C [1]. These ecosystems are of considerable ecological and socioeconomic importance, particularly in tropical island nations, where they support fisheries, provide protein resources, and protect coastlines from wave energy.

In Malaysia, reef systems are predominantly fringing reefs associated with islands, while East Malaysia supports comparatively higher coral diversity. Reef development along the Strait of Malacca is relatively limited by elevated sedimentation and water turbidity, which reduce coral cover and species richness [2-4]. Nevertheless, key reef areas exist in Langkawi and Pulau Payar in Kedah, Pulau Jarak and the Sembilan Archipelago in Perak [5, 6]. Malaysia also supports high reef-associated fish diversity, with approximately 712 marine fish species recorded, many of which are closely linked to coral reef habitats [7]. However, compared with the east coast of Peninsular Malaysia, reef fish communities on the west coast remain understudied [8], resulting in significant knowledge gaps regarding reef ecosystem condition in this region.

The Sembilan Archipelago (SA) comprises nine uninhabited islands, Pulau Agas, Pulau Batu Hitam, Pulau Batu Putih, Pulau Buluh, Pulau Lalang, Pulau Nipis, Pulau Payung, Pulau Rumbia, and Pulau Saga, located in the Strait of Malacca off the west coast of Peninsular Malaysia, located in the Strait of Malacca along the western coast of Peninsular Malaysia. In 2010, the islands were designated as a state park to promote conservation and ecotourism development [9]. However, the

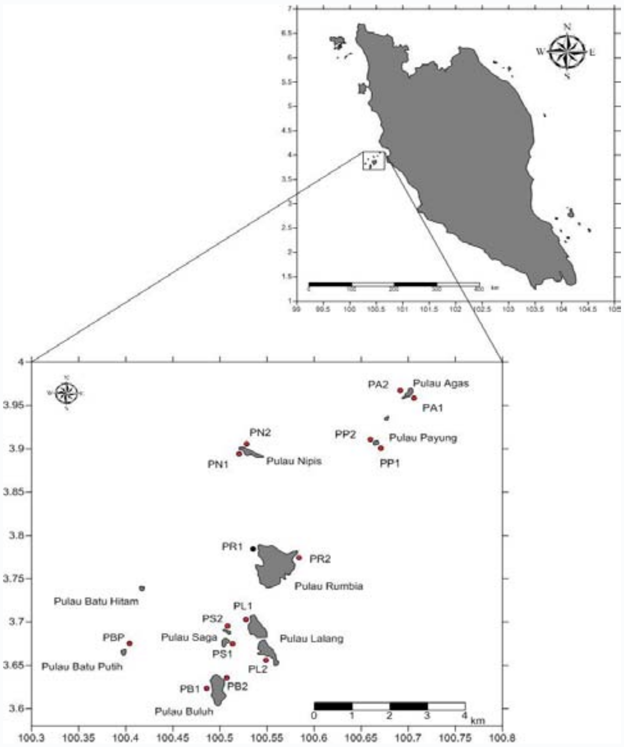

Figure 1: Location map of the SA with sampling sites marked as red dots.

ecosystem is currently facing multiple pressures, including declining fishery resources, conflicts over fishing restrictions, and increasing impacts from tourism activities [10]. Overexploitation of key commercial species, such as groupers and snappers, further threatens the stability of reef ecosystems and trophic balance [11].

Reef fish communities are a significant ecological element of coral reefs, contributing to energy transfer, trophic dynamics, and ecosystem resilience [12]. Globally, reef fisheries and ornamental fish trades provide important economic benefits but also exert increasing pressure on reef systems [13, 14]. Biodiversity within reef systems is broadly regarded as an important measure of ecosystem health and stability [15]. Reef fish biomass and diversity are generally higher in undisturbed or protected reef systems, whereas degraded reefs often exhibit reduced diversity and dominance by a few tolerant species [16]. Overall syntheses estimate more than 1,000 reef-associated fish species across Malaysia [8].

Even though the SA holds considerable ecological and economic value, comprehensive assessments integrating coral reef condition and reef fish community structure remain limited. Previous studies have primarily focused on coral condition and fish assemblages independently, without a holistic ecosystem-level approach. Such integrated assessments are essential for accurately evaluating reef health and predicting ecosystem resilience [17, 18].

In this context, the Coral Health Index (CHI) provides a valuable framework for assessing reef ecosystem condition. The CHI is a composite index that integrates key ecological components, namely coral cover, fish biomass, and microbial indicators such as *Vibrio* abundance [19]. By combining multiple diagnostic parameters, the CHI offers a more comprehensive assessment of reef health than single-metric approaches. Even when one component exhibits low values, the overall index may still indicate recovery potential, making it useful for evaluating both current status and future trajectories of reef ecosystems.

Accordingly, this study aims to assess the SA's reef condition and fish assemblages using integrated ecological indicators, including benthic cover, fish biomass, and coral health status, based on the CHI framework. The findings are expected to provide a comprehensive baseline for reef ecosystem health in the Strait of Malacca and support future conservation planning, fisheries governance, and Marine Protected Area (MPA) proposals in Perak waters.

Materials and Methods

Study area

Field assessments were performed in September and October 2020 across the SA. The islands are situated approximately 10-20 km offshore from Lumut, Perak. They are largely uninhabited, with minimal infrastructure except for a small monitoring station on Pulau Lalang managed by the Perak State Parks Corporation. The absence of formal MPA status means that fishing and tourism activities are carried out with limited regulation in the archipelago.

A total of 15 underwater sampling stations were selected across the archipelago, with two stations each at Pulau Agas (PA), Pulau Buluh (PB), Pulau Lalang (PL), Pulau Nipis (PN), Pulau Payung (PP), Pulau Rumbia (PR), and Pulau Saga (PS), and one station at Pulau Batu Putih (PBP) (Figure 1). No sampling was conducted at Pulau Batu Hitam due to safety constraints.

Benthic sampling and coral community assessment

Benthic communities were assessed using the Point Intercept Transect protocol following Hill and Wilkinson [20]. Each station involved the placement of two 50 m transects parallel to the shoreline at a depth of 5-10 m, with underwater visibility recorded as below 5 m. All sessile benthic organisms beneath each transect line were

Table 1: Coral morphology was classified following Edinger and Risk [17].

Group	Morphology	Category Characteristics
R	Acroporids	Branching, bushy, radiate, table/flat, and submassive *Acropora* species
	Table/flat coral	Non-*Acropora* species with table/flat shapes, e.g., *Montipora*
	Millepora & *Heliopora*	Fire corals and blue corals (hydrocorals)
K	Branching coral	Branching non-*Acropora* species, e.g., *Porites cylindrica* and *Pocillopora*
	Encrusting coral	Corals that attach to the substrate, usually forming small colonies
	Leaf-like coral	Non-*Acropora* species with vertical or horizontal leaf shapes, e.g., *Echinopora*, *Pavona*
	Fungiids	Free-living mushroom corals
S	Massive plate coral	Large massive plate-forming corals, e.g., *Euphyllia* and *Lobophyllia*
	Massive coral	Ball- or boulder-shaped coral species
	Submassive coral	Lobed or bumpy coral species, sometimes columnar, e.g., *Goniopora* and *Galaxea*

recorded at 1 m intervals, with observations made within a 0.25 m radius of each point following Ismail and Khoo [21].

Identification of coral colonies was conducted to the minimum genus level based on taxonomic references from Corals of the World [22] and supported by photographic documentation and identification guides [6, 23]. Benthic categories included hard corals, soft corals, dead corals (recent mortality and rubble), Crustose Coralline Algae (CCA), other biota (e.g., macroalgae, sponges), and abiotic substrate (sand, silt, rock).

The assessment of coral reef health employed Live Coral Cover (LCC) following Chou *et al.,* [24] coral cover classification scheme and the Coral Health Index (CHI) introduced by Kaufman *et al.,* [19]. LCC values were grouped into Poor, Fair, Good, and Excellent categories based on percentage ranges of 0-25%, 26-50%, 51-75%, and 76-100%, respectively, while CHI values were ranked from Very degraded to Very healthy across a 0-1 scale.

Reef fish sampling and biomass estimation

The study assessed reef fish communities using the Underwater Visual Census (UVC) protocol outlined by Labrosse *et al.,* [25] along the same depth range (5-10 m). At each station, two replicate 50 m belt transects were surveyed, each covering an effective area of 250 m^2 (50 m × 5 m belt width). A 15-minute acclimatisation period was observed before each survey to minimise diver-induced behavioural disturbance.

Fish were recorded if they occurred within 2.5 m on each side of the transect and within a 5 m vertical zone above the line. Data collected included species composition, abundance, size estimates, and photographic/video documentation. Surveys were conducted continuously along each transect at a slow swimming pace, as suggested by Pais and Cabral [26].

Fish species were identified using standard taxonomic references [27, 28] and validated using online databases [29].

The biomass of fish was calculated using the equation $W = aL^b$, where wet weight (*W, g*) was derived from total fish length (L, cm) using species-specific coefficients a and b obtained from FishBase [29]. Biomass was standardised as g m^{-2} based on the surveyed area of 250 m^2 per transect.

Biodiversity and community analyses

Coral and fish community structure were analysed using standard ecological indices. These included Shannon-Wiener diversity *(H')*, Margalef richness index *(d)*, and Pielou's evenness index *(J')*. Coral Mortality Index (MI) was determined as the proportion of dead coral relative to total coral cover, with thresholds above 0.33 indicating degraded conditions [30]. Relative Abundance (RA) of taxa was classified into standard categories ranging from rare to dominant [31].

Coral community structure was further analysed using morphology-based classification and *r-K-S* ecological strategies following Edinger and Risk [17], with conservation classes (C1-C4) assigned based on dominant coral growth forms (Table 1).

Microbial analysis

Microbial samples were collected using sterile bottles that were submerged to a depth of <1 m and filled underwater to avoid contamination. Samples were sealed, stored at low temperature, and analysed promptly. Triplicate 1 ml aliquots of each sample were cultured on Compact Dry VP (CDVP) plates. CDVP contains selective culture components for detecting *Vibrio* spp. After incubation at 35°C for 24 hours, colonies were manually counted and recorded as CFU/ml.

CHI assessment

The CHI served as the basis for reef health evaluation by integrating ecological and microbial factors, including benthic condition and fish biomass [19]. Each component was normalised to a 0-1 scale.

For benthic assessment, CHI was estimated from the contribution of hard corals and crustose coralline algae relative to total substrate cover. For fish, CHI was calculated by standardising fish biomass against a reference value of 500 g m^{-2}:

CHIfish = Fish biomass/500

For the microbial component, CHI was calculated based on *Vibrio* abundance using an inverse transformation of Colony-Forming Units (CFU):

CHImicrobes = ((average CFU/100)+1)$^{-1}$

The overall CHI was computed as the mean of the three components:

CHI = (CHIbenthos + CHIfish + CHImicrobes)/3

Reef health was then classified into five categories based on CHI values, from very degraded to very healthy.

Results

Benthic composition and coral community structure

In total, 30 benthic transects were conducted across 15 sampling stations in the SA. The recorded LCC for both hard and soft corals ranged from 9.60% to 35.84%, with a mean value of 26.05% (Figure 2). The highest LCC was recorded at site PP2 (Pulau Payung, 35.84%), while the lowest was observed at PB2 (Pulau Buluh, 9.60%). The latter site also exhibited the highest dead coral cover (30.40%). Based on LCC classification, seven sites were categorized as having "fair" coral cover, while the remainder were classified as "poor"; no sites fell into the "good" category. Crustose Coralline Algae (CCA) cover was generally low, with the highest value recorded at PP2 (12.14%), while no CCA was observed at Pulau Nipis.

Throughout the archipelago, 46 species of hard corals representing 21 genera and 11 families were observed, along with 12 genera of soft corals (Table 2). Pulau Lalang exhibited the highest species richness (27 species), while Pulau Batu Putih, Pulau Buluh, and Pulau Rumbia recorded the lowest richness (16 species each). *Diploastrea heliopora* was the only species recorded on all islands. The most dominant hard coral families were *Poritidae* (23.01% mean cover), followed by *Acroporidae* (16.45%), *Dendrophylliidae* (13.11%), and *Merulinidae* (11.08%).

The most frequently encountered species included *Diploastrea heliopora* (8.51%), *Tubastraea aurea* (7.10%), and *Porites lutea* (5.42%). Soft coral assemblages were dominated by *Zoanthus* spp. (7.05%) and *Junceella* spp. (5.62%). Several species exhibited restricted distributions, with *Acropora florida, A. hyacinthus*, and *A. robusta* recorded only at Pulau Payung, Pulau Rumbia, and Pulau Saga, respectively. Soft coral genera such as *Discosoma* and *Sinularia* were similarly restricted to Pulau Lalang and Pulau Rumbia, respectively.

Coral reef condition

The Coral Mortality Index (MI) indicated generally degraded conditions across the archipelago, with elevated values recorded at Pulau Buluh (0.45) and Pulau Nipis (0.42), while all other islands recorded MI values below 0.30. Coral diversity (Shannon–Wiener index, *H'*) ranged from 2.24 to 2.78, with the highest diversity at Pulau Lalang. Evenness values ranged from 0.81 to 0.93, indicating relatively uniform species distribution across most sites, with Pulau Rumbia showing the highest evenness (0.93) (Table 3).

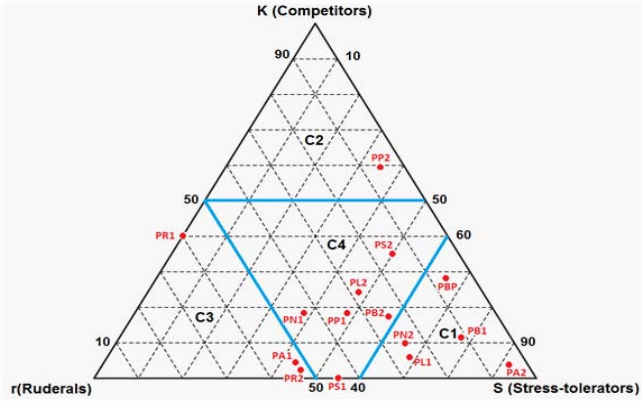

Figure 3: Coral morphological classes for 15 reef sites in the SA.

Coral community morphology analysis revealed variation in ecological strategies across sites (Figure 3). Five locations were classified as stress-tolerant-dominated (C1), one site as branching/acroporid-dominated (C2), two sites as Acropora-dominated (C3), and the remaining sites as mixed assemblages (C4), indicating heterogeneous reef conditions across the archipelago.

Reef fish diversity and abundance

Surveys conducted across 30 belt transects, each measuring 250 m^2, covered a total area of 7,500 m^2 and documented 17,303 reef fish individuals belonging to 50 taxa and 24 families (Table 4). The order *Perciformes* was most diverse (43 species, 18 families), followed by *Tetraodontiformes*. According to the IUCN Red List of Threatened Species, all observed fish were classified as Least Concern (LC).

Fish assemblages were strongly dominated by the family Pomacentridae, accounting for 12,570 individuals (>50% of total abundance). Other common families included *Nemipteridae, Apogonidae, Lutjanidae*, and *Serranidae*, while *Syngnathiformes* showed the lowest abundance (3 individuals overall), indicating highly uneven community structure.

The diversity analysis showed Shannon-Wiener (*H'*) values ranging from 0.42 at PBP to 1.93 at PS1. Margalef richness (*d*) ranged from 2.30 to 7.60, whereas Pielou's evenness (*J'*) values were between 0.20 and 0.75 (Table 5). Pulau Lalang exhibited the highest overall fish diversity, followed by Pulau Saga, while Pulau Batu Putih consistently

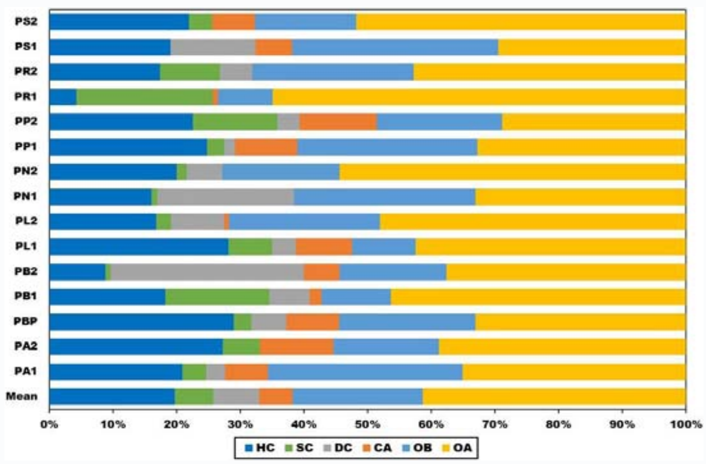

Figure 2: Percentage of benthic components in the SA.

Table 2: Summary of coral colony relative abundance and mean percentage in the SA.

No.	Family / Genus / Species	PA	PBP	PB	PL	PN	PP	PR	PS	Mean (%)
	HARD CORALS									
	Acroporidae									**16.45**
1	*Acropora clathrata*				***	***				0.78
2	*A. muricata*					***		***	****	2.12
3	*A. florida*						***			0.22
4	*A. hyacinthus*							***		0.94
5	*A. robusta*								**	0.06
6	*Acropora* spp.		***	***		***				1.05
7	*Montipora danae*	***		**			***	***		1.91
8	*M. hispida*			***	***	***		***	****	4.73
9	*Montipora* spp.	***	***		***	****		***		4.63
	Agariciidae									**1.94**
10	*Pavona decussata*		***		***	***		**	***	1.94
	Dendrophylliidae									**13.11**
11	*Duncanopsammia peltata*	***	***	**	***	***	***	***		2.13
12	*Tubastrea aurea*	***	****	***	***	***	*****		***	7.10
13	*T. micranthus*	***	***				***		***	2.23
14	*Turbinaria frondens*	**		***	***	***				0.86
15	*T. reniformis*				***	***	**		***	0.79
	Diploastreidae									**8.51**
16	*Diploastrea heliopora*	***	***	****	****	****	**	**	****	8.51
	Fungiidae									**1.60**
17	*Fungia fungites*			***	***	***				1.60
	Leptastreidae									**0.73**
18	*Leptastrea purpure*a						***			0.24
19	*L. transversa*	***					**		***	0.49
	Lobophylliidae									**2.50**
20	*Acanthastrea rotundoflora*						***			0.22
21	*Lobophyllia corymbosa*			***						0.19
22	*L. hemprichii*			***						0.19
23	*L. radians*				**			***		0.48
24	*L. recta*		***	***		***		**	***	1.43
	Merulinidae									**11.08**
25	*Cyphastrea chalcidicum*	***			**	**	***			0.90
26	*C. serailia*						**			0.13
27	*Dipsastraea speciosa*		***							0.07
28	*Dipsastraea* spp.	***	***		***	***		***	***	2.26
29	*Favites abdita*			***	***	***				1.68
30	*F. pentagona*		***		***	***	***	***	***	2.04
31	*Favites* spp.	***	***		***		***	***		1.72
32	*Goniastrea edwardsi*				***					0.14
33	*G. pectinata*		****		**				**	0.80
34	*Hydnophora microconos*				**			***		0.28
35	*Mycedium elephantotus*	***		***			***		**	1.05
	Pocilloporidae									**0.56**
36	*Pocillopora damicornis*		***		***					0.56
	Poritidae									**23.0**1

37	*Goniopora columna*	*****	***	***			**			3.85
38	*G. djiboutiensis*	***							**	0.18
39	*G. lobata*						***			0.27
40	*Goniopora* spp.	****			**		**			1.50
41	*Porites lobata*				***	***	****		***	4.15
42	*P. lutea*			****	***	****	****	**	***	5.42
43	*P. rus*				***			***		1.00
44	*Porites* spp.	***	****	****	****				***	6.65
	Psammocoridae									**0.72**
45	*Psammocora contigua*				***					0.27
46	*P. profundacella*	***			**					0.45
	No. of species recorded	17	16	16	27	19	20	16	18	46
	SOFT CORALS									
1	*Dendronephthya*		***					**		0.41
2	*Diodogorgia*	**					***			0.30
3	*Discosoma*				**					0.07
4	Gorgonian							***		0.22
5	*Junceella*	***	***	***	***		****	***	**	5.62
6	*Lobophytum*							****	***	2.89
7	*Rhodactis*	**			**				***	0.33
8	*Pachyclavularia*				***	***				0.51
9	*Palythoa*						***			0.29
10	*Sarcophyton*	**		***		***		***		1.89
11	*Sinularia*							***		0.21
12	*Zoanthus*		***	****		***	***	*****	***	7.05
	No. of genera recorded	4	3	3	4	3	4	7	4	12

Notes: -no record, *rare, **uncommon, ***common, ****abundant, *****dominant

Table 3: Diversity (*H'*), Evenness, and Mortality (MI) Indices in each island of the SA.

Island	Species No.	*H'*	Evenness	MI
Pulau Agas	17	2.45	0.86	0.05
Pulau Batu Putih	16	2.24	0.81	0.15
Pulau Buluh	16	2.55	0.90	0.45
Pulau Lalang	27	2.78	0.83	0.18
Pulau Nipis	19	2.58	0.88	0.42
Pulau Payung	20	2.44	0.81	0.09
Pulau Rumbia	16	2.59	0.93	0.08
Pulau Saga	18	2.54	0.88	0.22
SA	46	3.25	0.85	0.17

recorded the lowest values across indices. Station-level patterns showed the highest diversity and richness at PS1 and the strongest dominance at PBP.

Fish abundance varied substantially among stations, with a maximum of 2,513 individuals recorded at PP2 and a minimum of 235 individuals at PL2. Biomass ranged from 3.52 g/m^2 (PR1) to 105.05 g/m^2 (PP2) (Table 5). At the island scale, Pulau Payung recorded the highest fish biomass, while Pulau Rumbia exhibited the lowest.

Distribution and abundance of *Vibrio* spp.

The *Vibrio* colony data from replicate sampling sites in the SA were averaged and summarised in Table 6, with a mean total count of 291 CFU/ml. A total of 119 CFU/ml of *Vibrio*, representing 40.89% of the mean total colony count, produced blue-green colonies. Meanwhile, 172 CFU/ml of *Vibrio*, representing 59.11% of the mean total colony count, produced grey or yellow colonies.

Through this study, PS1 had the highest distribution and abundance of *V. parahaemolyticus*, with 53 CFU/ml. Meanwhile, PB1 showed the highest abundance of *Vibrio* spp., reaching 73 CFU/ml. The highest mean total colony count of *Vibrio* spp. was also recorded at PB1, with 89 CFU/ml.

Coral health assessment

Coral reef health assessment using the CHI for benthic components further supported the finding of degraded conditions across the archipelago. The mean CHI for benthos was 0.26, with three islands (Pulau Buluh, Pulau Nipis, and Pulau Rumbia) classified as "very degraded" (CHI <0.20), while all remaining islands were categorized as "degraded" (CHI <0.40).

Fish-derived CHI values showed strong spatial variability, ranging from 0.01 (PR1) to 0.21 (PP2). At the island scale, Pulau Payong recorded the highest mean CHI (0.14), followed by Pulau Buloh (0.07), while Pulau Rumbia showed the lowest (0.01). These results indicate that fish biomass contributes unevenly to reef health across the archipelago.

For *Vibrio*, most Sembilan Islands sites showed a very healthy

Table 4: Recorded fish species from the SA waters.

Family	Species	IUCN
Holocentridae	*Sargocentron sp.*	LC
Engraulidae	*Encrasicholina sp.*	LC
Apogonidae	*Ostorhinchus angustatus*	LC
	Pristicon trimaculatus	LC
	Rhabdamia sp.	LC
Caesionidae	*Caesio caerulaurea*	LC
	Caesio teres	LC
	Pterocaesio chrysozona	LC
	Pterocaesio digramma	LC
Carangidae	*Gnathanodon speciosus*	LC
Chaetodontidae	*Chaetodon collare*	LC
	Chaetodon octofasciatus	LC
	Heniochus acuminatus	LC
Diodontidae	*Diodon sp.*	LC
Epinephelidae	*Cephalopholis boenak*	LC
	Cephalopholis formosa	LC
	Cephalopholis microprion	LC
Haemulidae	*Plectorhinchus sp.*	LC
Labridae	*Halichoeres nebulosus*	LC
	Halichoeres nigrescens	LC
	Labroides dimidiatus	LC
	Thalassoma lunare	LC
Liopropomatidae	*Diploprion bifasciatus*	LC
Lutjanidae	*Lutjanus lemniscatus* *Lutjanus vitta*	LC LC
Malacanthidae	*Malacanthus brevirostris*	LC
Monodactylidae	*Monodactylus argenteus*	LC
Mullidae	*Upeneus asymmetricus*	LC
Nemipteridae	*Scolopsis affinis*	LC
	Scolopsis ciliata	LC
	Scolopsis trilineata	LC
	Scolopsis vosmeri	LC
Ostraciidae	*Ostracion cubicum*	LC
Pomacanthidae	*Pomacanthus annularis*	LC
Pomacentridae	*Abudefduf bengalensis*	LC
	Abudefduf vaigiensis	LC
	Amphiprion sandaracinos	LC
	Chromis viridis	LC
	Neoglyphidodon melas	LC
	Neoglyphidodon nigroris	LC
	Neopomacentrus azysron	LC
	Neopomacentrus cyanomos	LC
Pempheridae	*Pempheris oualensis*	LC
Scaridae	*Scarus ghobban*	LC
Siganidae	*Siganus canaliculatus*	LC
	Siganus guttatus	LC
	Siganus javus	LC
Zanclidae	*Zanclus cornutus*	LC
Syngnathidae	*Doryrhamphus janssi*	LC
	Trachyrhamphus longirostris	LC

Table 5: Diversity indices and biomass (g/m^2) of reef fish in the SA.

Sites	*H'*	*d*	*J'*	Biomass
PA1	0.75	5.93	0.25	31.67
PA2	1.61	5.73	0.59	16.50
PBP	0.42	2.30	0.20	13.51
PB1	1.76	3.91	0.71	22.27
PB2	1.02	7.46	0.32	43.42
PL1	1.92	4.57	0.75	16.02
PL2	1.38	6.36	0.48	20.46
PN1	0.98	5.12	0.35	29.31
PN2	1.88	7.16	0.62	33.19
PP1	0.80	5.03	0.28	38.50
PP2	1.31	5.45	0.45	105.05
PR1	1.20	4.63	0.48	3.52
PR2	1.87	5.23	0.71	10.40
PS1	1.93	7.60	0.62	32.83
PS2	1.15	6.60	0.37	28.50

Table 6: Average *Vibrio* colonies (CFU/ml) and CHI in the SA.

Sites	*V. parahaemolyticus*	*Vibrio* spp.	Total *Vibrio*	CHI
PA1	2	2	4	0.96
PA2	5	24	29	0.78
PBP	1	0	1	0.99
PB1	16	73	89	0.53
PB2	5	0	5	0.95
PL1	13	26	39	0.72
PL2	4	3	7	0.93
PN1	2	12	14	0.88
PN2	0	3	3	0.97
PP1	1	1	2	0.98
PP2	5	4	9	0.92
PR1	9	13	22	0.82
PR2	1	5	6	0.94
PS1	53	0	53	0.65
PS2	1	6	7	0.93
Total	119	172	291	

CHI (0.80-1.00), except PA2, PS1, and PL1, which were classified as healthy (0.60-0.79). Also, only PB1 was at a moderately healthy CHI level within the range (0.40-0.59) (Table 6).

The total Coral Health Index values, combining benthos, fish, and microbial components, ranged from 0.33 to 0.46, with an overall mean of 0.39 (Table 7). Based on CHI classification, three islands (Pulau Agas, Pulau Batu Putih, and Pulau Payung) were categorized as "moderately healthy," while all other islands were classified as "degraded." No island achieved "healthy" or "very healthy" status.

Table 7: Compilation of CHI values for benthic communities, fish, and microbes.

Island	Benthos	Fish	*Vibrio*	CHI	Status
Pulau Agas	0.31	0.05	0.87	0.41	Moderate
Pulau Batu Putih	0.33	0.03	0.99	0.45	Moderate
Pulau Buluh	0.17	0.07	0.74	0.33	Degraded
Pulau Lalang	0.26	0.04	0.83	0.38	Degraded
Pulau Nipis	0.17	0.06	0.92	0.38	Degraded
Pulau Payung	0.30	0.14	0.95	0.46	Moderate
Pulau Rumbia	0.10	0.01	0.88	0.33	Degraded
Pulau Saga	0.25	0.06	0.79	0.37	Degraded
SA	0.26	0.06	0.86	0.39	Degraded

Overall, the SA is characterised by degraded coral reef conditions, with limited spatial pockets of moderate ecological condition.

Discussion

Coral reef ecosystems in the SA are influenced by a combination of natural and anthropogenic stressors, with sedimentation as a key driver of reef degradation along the Strait of Malacca [2, 32]. Elevated turbidity associated with coastal development and human activities in adjacent areas such as Lumut and Pulau Pangkor has reduced light availability and increased sediment deposition, both of which negatively affect coral growth, survival, and reef development [5, 33]. These conditions have resulted in generally sparse reef structures and limited reef accretion potential in the region.

Coral reef condition

LCC ranged from poor to fair, with most sites classified as poor and only a few as fair. The mean LCC (26.05%) was substantially lower than values reported for protected reef systems such as Pulau Payar Marine Park (33.05%) [34] and below the national average in Malaysia in 2020 (41.32%) [11]. However, it was comparable to that of other unprotected west coast reefs such as Pulau Songsong (25.18%) [35], indicating that the reef condition in the SA is consistent with other disturbed systems in the Strait of Malacca [36].

Although LCC values show slight improvement compared to earlier studies [5], the increase remains marginal and may reflect methodological differences rather than substantial ecological recovery. The relatively low percentage of dead coral (5.44%) suggests past mortality events, with the remaining reef structure persisting as a remnant framework. The Coral Mortality Index (MI = 0.17) indicates that reefs are not currently in a critical mortality phase, as stated by Gomez *et al.,* [30]. However, continued environmental stress could reverse this condition. Overall, a benthic CHI of 0.26 suggests deteriorating reef conditions and limited resilience to ongoing pressures.

Coral diversity and composition

Despite degraded conditions, the SA supports relatively high coral diversity, with 46 hard coral species recorded, representing a substantial proportion of known west coast diversity [37]. However, genus-level diversity remains lower than that of protected systems such as Pulau Payar Marine Park [34], highlighting the influence of protection status on biodiversity maintenance.

Community structure is dominated by massive and stress-tolerant coral forms, particularly *Diploastrea heliopora* and *Porites* spp., which are well adapted to high turbidity and sediment loads. A comparable pattern has been reported in other regional turbid reef habitats [2, 38, 39]. In contrast, sediment-sensitive genera such as *Acropora* are present only in low abundance, reflecting their limited tolerance to degraded environmental conditions [40]. Coral assemblages are therefore indicative of ecological filtering driven by environmental stress, favouring resilient taxa.

Reef fish community structure and habitat linkages

Reef fish assemblages in the SA exhibited low diversity and strong taxonomic dominance, particularly by Pomacentridae. Shannon-Wiener diversity values were generally low (0.42-1.93), indicating simplified community structure compared to healthy reef systems, where values typically exceed 3 [41]. This pattern points to a simplification or degradation of reef fish assemblages within the study area.

Fish diversity and richness patterns were closely associated with habitat condition, particularly live coral cover. Sites with higher coral cover supported greater species richness, whereas degraded sites exhibited reduced diversity and increased dominance by opportunistic species. The low abundance of coral-dependent indicator taxa, such as butterflyfish (Chaetodontidae), further supports the interpretation of reduced habitat quality.

Fish biomass was highly variable but generally low, and fish-based CHI values (0.01-0.21; mean 0.06) indicate poor ecological condition. Although the archipelago is uninhabited, fishing pressure and indirect anthropogenic impacts likely contribute to observed patterns. Selective fishing may also alter trophic structure, potentially reduce herbivory and further compromise reef resilience [42].

Coral Health Index (CHI) assessment and reef status

Application of the CHI provides an integrated assessment of reef condition across benthic, fish, and microbial components. This study represents one of the first applications of CHI in the SA, enabling a multi-dimensional evaluation of reef health. Results indicate that both benthic and fish components are under stress, with a mean CHI value of 0.39, classifying the reefs as degraded with low resilience potential.

Relative to non-protected Malaysian reefs, Langkawi reefs were classified near the lower boundary of fair condition based on CHI values [43]. This emphasises the need for proper management intervention. Without formal protection, the SA is likely to continue facing ecological stress from unregulated fishing and tourism.

Conclusion

Ecological assessments conducted in the SA revealed that coral reef ecosystems and reef fish communities are facing considerable environmental stress, with ecological conditions ranging from low to moderate at most sampling sites. The LCC and reef fish diversity were lower than those reported in nearby well-managed marine protected areas, with fish assemblages dominated by Pomacentridae, reflecting simplified community structure and reduced ecological complexity. Although some sites, particularly Pulau Payung, exhibited locally higher biomass and moderate coral productivity, overall results suggest a continuing decline in reef condition driven by persistent environmental pressures and limited management control.

The study also demonstrates the usefulness of the CHI as an integrated tool for assessing reef condition in Malaysian waters. By combining benthic, fish, and microbial components, the CHI framework provides a comprehensive evaluation of coral reef health and effectively distinguishes between moderately healthy and degraded reef systems. The application of CHI in this study highlights its potential for broader use in regional reef monitoring and conservation planning.

Despite spatial differences among islands, the overall ecological status of the SA indicates ongoing degradation, likely driven by sedimentation, fishing pressure, and anthropogenic impacts. The close linkage between coral condition and reef fish communities further emphasizes that continued decline in coral habitat quality will directly impact fish diversity and ecosystem functioning. Given the limited protection and management currently in place, reef ecosystems are likely to deteriorate further without effective intervention.

In light of these findings, there is an urgent need for comprehensive and coordinated conservation measures. To safeguard its coral reef ecosystems and associated biodiversity, the SA should be considered for MPA status. Such protection would not only help mitigate ongoing pressures but also support long-term ecological recovery, sustainable fisheries practices, and marine preservation efforts within the Strait of Malacca. Continued research and focused management interventions are necessary to sustain these reef systems for future generations.

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Author Contributions

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Ethics Statement

The authors affirm that this research complies with the relevant ethical guidelines for research and publication.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Declaration of Competing Interests

The authors declare no conflict of interest.

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