

Assessment of Coral Reef Conditions and Resilience in Eastern and Northern Bali, Indonesia

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ABSTRACT

Across the Indo-Pacific, coral reef condition is increasingly affected by human pressures, land-based pollution, and climate-related stressors, including bleaching events. These challenges threaten biodiversity and the ecological services provided by coral reefs. This study aimed to assess coral health and recovery potential in East and North Bali and provide baseline data for conservation and management strategies. The research was conducted from June to November 2023 at seven reef sites, consisting of three sites in East Bali and four sites in North Bali. Benthic composition and live coral cover were assessed using the Underwater Photo Transect method, while reef fish abundance and biomass were evaluated using the Underwater Visual Census method. Site-level values were used to calculate coral cover, reef fish parameters, and Coral Health Index scores. Live coral cover ranged from 13.14% to 38.77% with regional means of 19.40% in East and 25.94% in North Bali; however, the difference was not statistically significant ($p = 0.9998$). A total of 380 reef fish representing 30 species and six families were recorded, comprising 85 individuals in East Bali and 295 in North Bali. Reef fish abundance also did not differ significantly between regions ($p = 0.4277$). Acanthuridae was the dominant family. Coral Health Index scores ranged from 3 to 6, while reef fish biomass was classified as low at all sites. These findings provide baseline information to support long-term monitoring, site-specific management, and conservation prioritization for Bali's coral reef ecosystems.

Keywords: Bali Island, Coral health, Coral triangle, Reef fish, Reef resilience

INTRODUCTION

Coral reefs are remarkable and diverse underwater ecosystems formed by calcium carbonate structures produced by corals. They are among the most biologically diverse communities found in tropical and subtropical regions. These reefs provide habitat for at least 25% of marine species, including fish, echinoderms, crustaceans, mollusks, sponges, tunicates, and cnidarians (Burt *et al.*, 2012; Fisher *et al.*, 2015; Atmaja *et al.*, 2023; Putri

et al., 2026). In Indonesia, coral reefs are widely distributed across environmental conditions shaped by temperature, salinity, sedimentation, water currents, seawater circulation, and substrate quality (Hoegh-Guldberg *et al.*, 2017). Despite their broad distribution, coral reefs are widely recognized as ecosystems that are particularly susceptible to environmental change.

Bali is a major tourist destination known its prominent diving spots in Indonesia, supported

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Received 10 December 2025 / Accepted 30 June 2026

by its abundant natural coral reef ecosystems. Diving and snorkeling sites are widely distributed throughout East and North Bali (Wingit *et al.*, 2017; Naja *et al.*, 2021). These areas are characterized by coral reefs, relatively clear waters, and internationally recognized diving attractions, including the wreck of the Liberty in Tulamben, East Bali (Kurnia *et al.*, 2024). However, anthropogenic activities can contribute directly and indirectly to the degradation of coral reef ecosystems (Lamb *et al.*, 2014; Fudjaja *et al.*, 2020). This degradation can weaken corals' ability to withstand disease (Roth *et al.*, 2018), which may result from biological stressors such as bacteria, fungi, and viruses, as well as abiotic factors such as rising sea surface temperatures, increased ultraviolet radiation, and pollution (Lönnerstedt *et al.*, 2014; Tkachenko, 2023).

Coral reefs face growing threats from coastal development, resource exploitation, disease (Palupi *et al.*, 2018), and ship groundings (Idris *et al.*, 2020). Approximately 19% of reefs globally have been permanently destroyed, and more than 60% of the remaining reefs are currently at high risk from human activities (Baum *et al.*, 2015). Recent large-scale reef monitoring studies have emphasized the importance of integrated ecological indicators and long-term assessment frameworks for evaluating coral reef condition and supporting adaptive management in the Indo-Pacific region (Samoilys *et al.*, 2025). Coral reef health can be assessed through chemical, physical, and biological indicators, including reef fish assemblages. In this context, fish families such as Chaetodontidae, Pomacentridae, and Eupomacentridae, which are strongly associated with reef condition, may serve as reliable ecological indicators (Seraphim *et al.*, 2020; Bravo *et al.*, 2021).

In coral reef ecology, resilience refers to the capacity of a reef ecosystem to resist disturbance and recover its structure and function after stress (Bang *et al.*, 2021). Direct assessment of reef resilience generally requires temporal monitoring or process-based indicators such as coral recruitment, bleaching resistance, coral disease, macroalgae cover, coral diversity, and herbivore biomass (Maynard *et al.*, 2015). In this study, resilience is interpreted more specifically as recovery potential,

inferred from threshold-based Coral Health Index (CHI) indicators, including live coral cover, fleshy seaweed cover, rubble cover, and reef fish biomass.

Previous studies have assessed coral health using coral condition and reef fish diversity at several locations in Indonesia (Twinandia *et al.*, 2016; Shidqi *et al.*, 2018; Wulandari *et al.*, 2022; Giyanto *et al.*, 2023; Najmi *et al.*, 2023; Isdianto *et al.*, 2024). However, the coral reef of North and East Bali, despite their ecological and tourism importance, remain insufficiently studied. Therefore, this study aimed to assess coral reef health and provide baseline on coral reef condition and recovery potential using benthic cover, reef fish assemblage, reef fish biomass, and threshold-based Coral Health Index indicators. The results of the study serves as an initial assessment to support the development of more comprehensive and site-specific management strategies in the area.

MATERIALS AND METHODS

Study area

This study was conducted from June to November 2023 in the eastern and northern regions of Bali Island. East Bali comprised three study sites: Padang Bai (PB), Blue Lagoon (BL), and Jemeluk Bay (JB). North Bali consisted of four sites: Les (LS), Bondalem (BD), Pacung (PC), and Penimbangan (PN). All study sites are shown in Figure 1.

Sampling design

Coral reef

At each study site, coral reef benthic data were collected using the Underwater Photo Transect (UPT) method. A 50-m transect line was laid parallel to the reef contour at approximately 5–10 m depth, following the general reef slope. Transect locations were selected purposively to represent the dominant reef habitat at each site while avoiding extensive sandy areas and physically inaccessible reef sections. Along each transect, 50 photo frames were taken using a 58×44 cm quadrat. Photo frames

within each site were treated as subsamples and were averaged to obtain site-level values for all benthic categories prior to statistical analysis, in order to avoid pseudoreplication.

Coral reef benthic conditions were documented using the Underwater Photo Transect (UPT) method. A 58×44 cm quadrat was positioned at 1-m intervals along each transect, resulting in 50 photographs per site (Figure 2). Data collection was carried out by two divers: one positioned the quadrat along the transect, while the other took the photographs.

Each underwater photograph was processed using Coral Point Count with Excel Extensions (CPCe) 4.1, with 30 random points were automatically generated and assigned to corresponding benthic substrate or biota categories. The resulting data were used to quantify the percentage cover of each benthic category. The

combination of the Underwater Photo Transect (UPT) method and CPCe analysis enables quantitative benthic composition while reducing underwater observation time and improving consistency in coral identification (Schaduw *et al.*, 2020; Prasetya and Santoso, 2022)

Reef fishes

Fish observations were conducted along the same transect line used for benthic assessment. The abundance, biomass, and diversity of reef fish were assessed using the Underwater Fish Visual Census (UVC) method, based on previous research conducted at Gosong Island (Najmi *et al.*, 2023). This method enables in situ species identification and fine-scale characterization of reef fish assemblages (Wilson *et al.*, 2018; Cheal *et al.*, 2021).

Reef fish species were identified using a reef fish identification guide for Indonesian waters

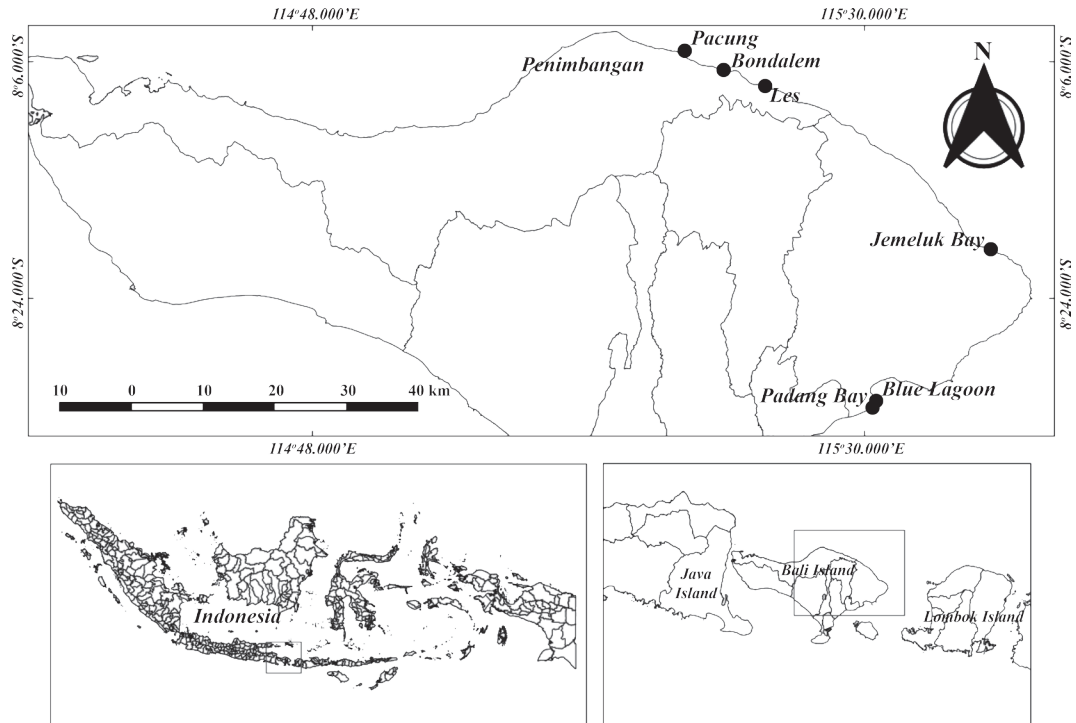


Figure 1. Locations of the seven coral reef study sites in eastern and northern Bali, Indonesia. Red circles indicate sites in East Bali, and green circles indicate sites in North Bali. The inset maps show the location of Bali within Indonesia and the study area on Bali Island.

(Allen and Adrim, 2003). Scientific names and family-level classifications of reef fishes were verified using FishBase (www.fishbase.se). Fish observations were divided into two size

classes: individuals > 10 cm in total length were recorded within a 2×50 m survey area, whereas individuals ≤ 10 cm were recorded within a 2.5×50 m survey area (Figure 3).

Underwater Photo Transect (UPT) Workflow

Benthic assessment and CPCe analysis

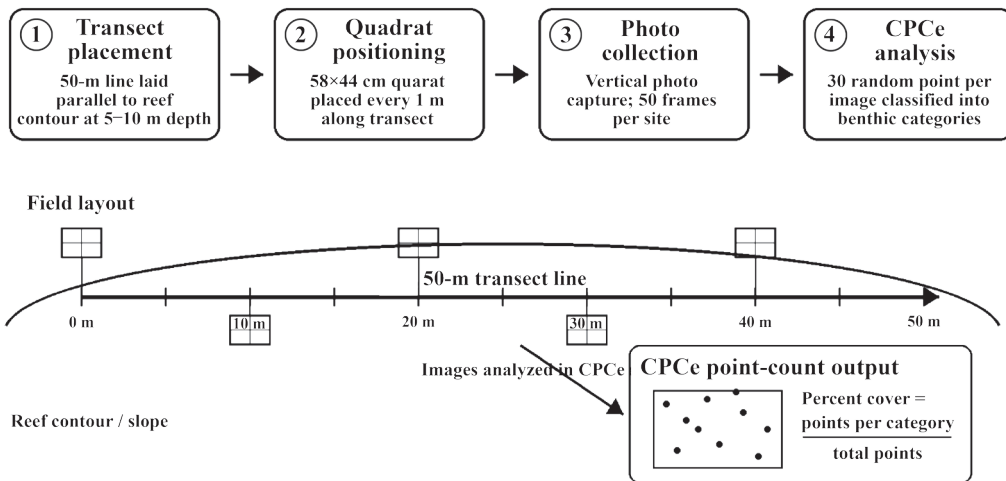


Figure 2. Workflow of the Underwater Photo Transect (UPT) method used to assess coral reef benthic composition. A 50-m transect line was positioned parallel to the reef contour at a depth of 5-10 m. A 58×44 cm quadrat was placed at 1-m intervals, producing 50 photographs per site. Each image was analyzed in CPCe using 30 randomly generated points to estimate the percentage cover of benthic categories.

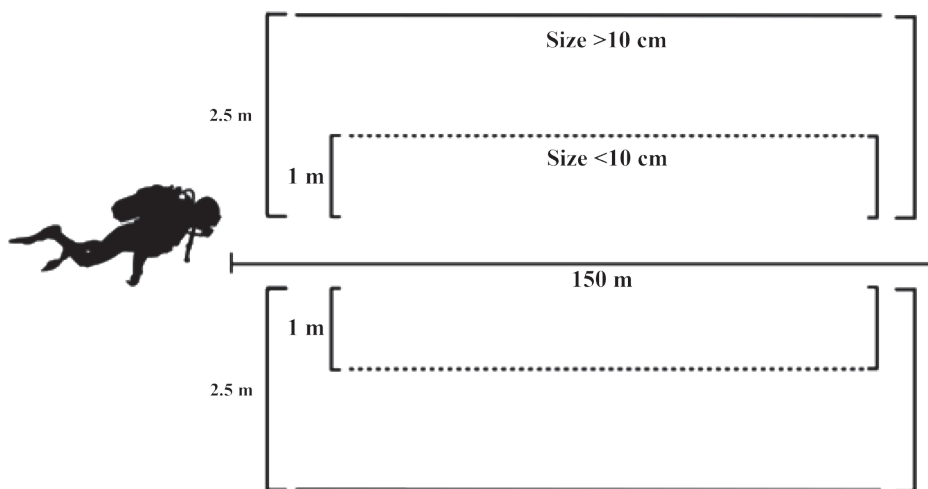


Figure 3. Schematic representation of the Underwater Visual Census (UVC) survey design used to assess reef fish communities. Reef fishes > 10 cm in total length were recorded within a 2.5-m belt on each side of the 150-m transect, whereas fishes < 10 cm were recorded within a 1-m belt on each side of the transect.

Data analysis

All data analyses accounted for the hierarchical structure of the sampling design. The 50 photographic frames collected along the transect were treated as subsamples rather than independent replicates. Data from the individual frames were aggregated to obtain one representative site-level value for each benthic category. Reef fish abundance and biomass were similarly calculated at the site level from the corresponding underwater visual census data. The seven study sites were subsequently treated as independent sampling units, provided that observations among sites were spatially independent, thereby avoiding pseudoreplication.

Descriptive statistics were calculated for all variables and are presented as mean values at the site level. Statistical comparisons between regions (Eastern and Northern Bali) were performed using site-level data only. All statistical analyses were conducted using IBM SPSS Statistics version 27, with a significance level set at $\alpha = 0.05$.

Coral reef cover percentage

The transect data were analyzed according to benthic cover categories. The recorded categories recorded included dead coral (DC), dead coral with algae (DCA), soft coral (SC), fleshy seaweed (FS), rubble (R), sand (S), silt (Si), and rock (RK). The percentage cover of each benthic category was calculated using the following equation:

$$N_i = \left(\frac{L_i}{n} \right) \times 100\%$$

where N_i is the percentage cover of benthic category, i ; L_i is the number of points assigned to category i ; and n is the total number of CPCe point analyzed per site.

CPCe point-count data were aggregated at the site level. For each site, 50 photographs, each containing 30 randomly generated, were analyzed, resulting in 1,500 classified points per site. Points assigned to each benthic category were summed across all photographs and divided by the total number of points per site to obtain

one representative percentage cover value for each category. These site-level values were used for descriptive analysis and regional comparison between East and North Bali.

Abundance of reef fishes

Reef fish abundance was calculated as the number of individuals recorded per unit survey area using the following formula:

$$X_i = \frac{n_i}{A}$$

where X_i is the abundance of reef fish ($\text{ind}\cdot\text{ha}^{-1}$); n_i is the number of type fish, and A described as area of observation. The observed number of individuals recorded for species or group i ; and A is the surveyed area. The observed number of individuals was first divided by the corresponding survey area to obtain density in $\text{ind}\cdot\text{m}^{-2}$, and then multiplied by 10,000 to convert the value to $\text{ind}\cdot\text{ha}^{-1}$.

Reef fish abundance and distribution data were analyzed descriptively using charts and tables in Microsoft Excel 2010 and IBM SPSS 27. Abundance was expressed as $\text{ind}\cdot\text{ha}^{-1}$ (Rosdianto *et al.*, 2021). Prior to statistical analysis, all data were tested for normality using the Shapiro-Wilk test and for homogeneity of variances using Levene's test. When these assumptions were met, one-way analysis of variance (ANOVA) was applied to test for differences in reef fish abundance between East and North Bali using site-level mean values. Statistical significance was set at $p < 0.05$. Because comparisons involved only two regions, post-hoc tests were not required. The ANOVA procedure followed established approach used in reef fish abundance studies (Hadi *et al.*, 2018).

Reef fish biomass

Reef fish biomass was estimated based on underwater visual census (UVC) data by converting visually estimated total length (TL, cm) of each individual into body mass using the length–weight relationship:

$$W = aL^b$$

where W is individual body mass (g); L is total length (cm); and a and b are species-specific constants. The length–weight parameters (a and b) for each species were obtained from FishBase (www.fishbase.se).

Individual fish masses were summed to obtain total biomass per site and subsequently standardized to kilograms per hectare ($\text{kg}\cdot\text{ha}^{-1}$) based on the total surveyed area. Biomass values were calculated for target reef fish families, including herbivorous (Acanthuridae, Scaridae, and Siganidae) and carnivorous groups (Serranidae, Lutjanidae, Lethrinidae, and Haemulidae), following the criteria used in the Coral Health Index framework (Giyanto *et al.*, 2023). The resulting site-level biomass values were used to calculate Coral Health Index (CHI) and for subsequent statistical analysis.

Coral reef health index

The Coral Reef Health Index (CHI) was derived using an integrated framework that combines benthic characteristics with reef fish attributes (Giyanto *et al.*, 2023). Within this framework, the benthic component reflects both current reef condition and recovery potential.

Reef condition was assessed based on live coral cover (LC) and classified into three distinct categories followed Giyanto *et al.* (2023): Low: $\text{HC} < 19\%$; Moderate: $19\% < \text{HC} < 35\%$; High: $\text{HC} > 35\%$.

Recovery potential was determined by integrating the percentage cover of fleshy seaweed (FS), rubble (R), rubble (R), and live coral (LC). These parameters were evaluated using predefined threshold criteria and subsequently classified into two resilience categories as follows:

Low: $\text{FS} > 3\%$ or $(\text{R} > 60\% \text{ and } \text{LC} < 5\%)$;

High: $\text{FS} \leq 3\%$ or $(\text{R} \leq 60\% \text{ or } \text{LC} \geq 5\%)$.

The reef fish component of the CHI was evaluated using biomass estimates of selected target fish families, comprising carnivorous groups (Serranidae, Lutjanidae, Lethrinidae, and Haemulidae) and herbivorous groups (Siganidae, Scaridae, and Acanthuridae), which were subsequently categorized

according to the criteria described below:

Low: $\text{biomass} < 970 \text{ kg}\cdot\text{ha}^{-1}$;

Moderate: $\text{biomass} = 970\text{--}1,940 \text{ kg}\cdot\text{ha}^{-1}$;

High: $\text{biomass} > 1,940 \text{ kg}\cdot\text{ha}^{-1}$.

Based on the established criteria, the overall index score was assigned as summarized in Table 1, with values ranging from 1 to 10. Higher index scores indicate better coral reef condition.

In this study, CHI scores were assigned by first classifying each site into three components: live coral cover, recovery potential, and reef fish biomass. These three categorical classification were then matched to the CHI matrix to determine the final score.

RESULTS AND DISCUSSION

Benthic components

Live coral cover (hard coral) ranged from 13.14% to 38.77% across the seven study sites, while the remaining benthic categories varied among sites (Figure 4). Mean live coral cover was higher in North Bali (25.94%) than in East Bali (19.40%). Mean soft coral and rubble cover in East Bali were 12.96% and 25.67%, respectively. The one-way analysis of variance (ANOVA) showed that live coral cover did not differ between East and North Bali ($p = 0.9998$). However, the finding should be interpreted cautiously because the analysis was based on a limited number of site-level observations after photographic-frame data were aggregated at each site.

Based on regional mean live coral cover, East Bali and North Bali were both classified as having moderate coral cover, with mean values of 19.40% and 25.94%, respectively. However, site-level live coral cover varied among sites, ranging from 13.14% to 38.77%. Low live coral cover was recorded at PB (13.14%), BL (16.33%), and PC (16.67%); moderate cover was recorded at JB (28.73%), LS (23.87%), and PN (24.47%); while BD showed high live coral cover (38.77%).

Table 1. Matrix used to calculate the Coral Reef Health Index (CHI) based on live coral cover, recovery potential, and reef fish biomass. Higher CHI scores indicate better overall reef condition.

Index	Benthic components		Fish components	Coral Health Index
	Live coral cover	Potential of recovery	Biomass of reef fish	
1	High	High	High	10
2	Moderate	High	High	9
3	High	High	Moderate	8
4	High	Low	High	8
5	Moderate	High	Moderate	7
6	Low	High	High	7
7	High	High	Low	6
8	High	Low	Moderate	6
9	Moderate	Low	High	6
10	Moderate	High	Low	5
11	Low	High	Moderate	5
12	Low	Low	High	5
13	High	Low	Low	4
14	Moderate	Low	Moderate	4
15	Low	High	Low	3
16	Low	Low	Moderate	3
17	Moderate	Low	Low	2
18	Low	Low	Low	1

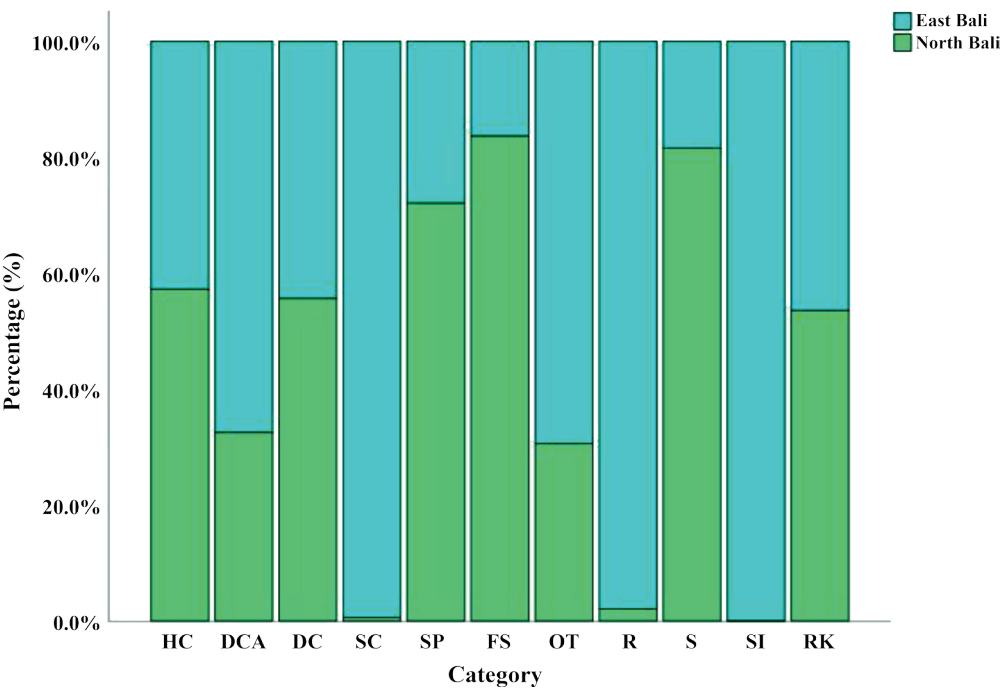


Figure 4. Percentage cover of benthic categories at the seven study sites in East and North Bali.
Note: HC = Hard coral; DCA = Dead coral with algae; DC = Dead coral; SC = Soft coral; SP = Sponges; FS = Fleishy seaweed; OT = Other; R = Rubble; S = Sand; Si = Silt; RK = Rock.

These values are comparable to those reported for several Indonesian reef systems classified as degraded to moderate or moderate in condition, including reefs in Papua (Hamuna *et al.*, 2020), the Spermonde Archipelago, Sulawesi (Yasir Haya and Fujii, 2020), Tunda Island, Banten (Mujiyanto *et al.*, 2020), and Karimunjawa, Central Java (Kennedy *et al.*, 2020). However, live coral cover in the present study was lower than the 53% reported for Moramo Bay (53%), a marine protected area in Southeast Sulawesi, Indonesia (Oetama *et al.*, 2024).

The moderate coral cover observed in both East and North Bali may reflect the influence of multiple environmental and anthropogenic stressors commonly reported in coral reef ecosystems, including tourism activities, coastal development, sedimentation, and physical reef disturbance. Similar patterns have been reported in Indonesian reef systems, where increased rubble and dead coral with algae have been associated with reef degradation and human activities (Oetama *et al.*, 2024).

In the present study, East Bali generally exhibited substantial rubble and soft coral cover, which may indicate previous physical disturbance

or partial reef degradation. Several northern sites also had moderate to high live coral cover, which may indicate differences in local reef conditions. Although these environmental drivers were not directly measured in this study, the observed benthic patterns are consistent with previous studies describing ecological pressures on Indonesian coral reef ecosystems.

Reef fish components

Across all seven study sites, a total of 380 reef fish individuals representing 30 species and six families were recorded. Of these, 85 individuals were recorded across the three sites in East Bali and 295 across the four sites in North Bali (Figure 5). Because the two regions contained different numbers of study sites, these pooled totals should not be interpreted as a direct regional comparison of abundance. One-way ANOVA indicated that standardized site-level reef fish abundance did not differ significantly between East and North Bali ($p = 0.4277$) Figure 6. Six families were recorded in North Bali, where Acanthuridae was represented by nine species and 260 individuals. Five families were recorded in East Bali, where Acanthuridae was also dominant, with eight species and 42 individuals (Table 2).

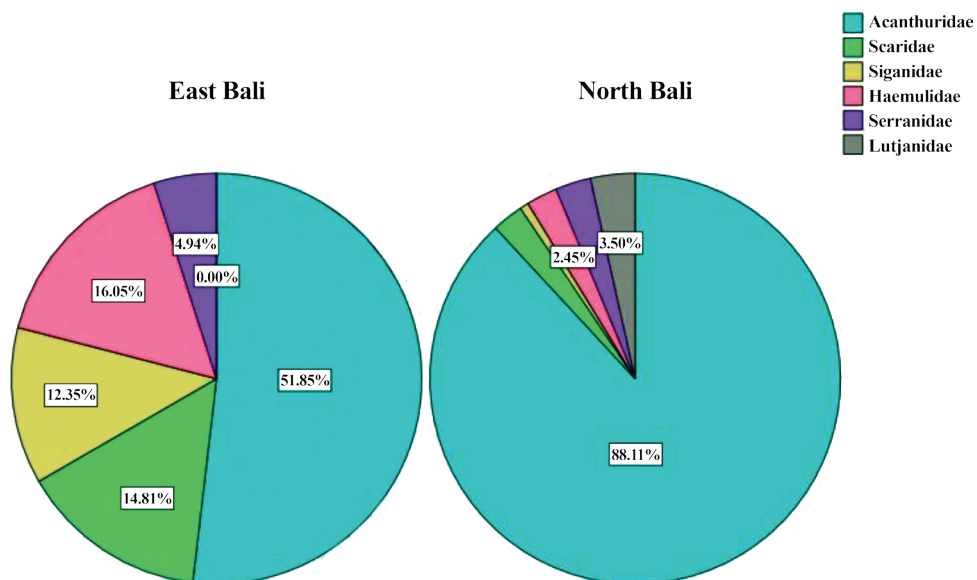


Figure 5. Relative composition of reef fish families recorded in East Bali and North Bali.

The dominance of Acanthuridae in this study is consistent with findings from reef fish surveys in Aceh (Ulfah *et al.*, 2019) and Southeast Sulawesi (Muis *et al.*, 2019). Previous studies recorded 426 individuals in Aceh, 181 individuals in Southeast Sulawesi, and 342 individuals in

Taka Bonerate National Park (Faricha *et al.*, 2020). However, direct comparisons of total individual counts should be interpreted cautiously because reef fish observations are influenced by survey effort, transect dimensions, habitat characteristics, environmental conditions, and sampling design.

Table 2. Estimated biomass, total length, and number of reef fish recorded in East and North Bali. Values are presented as mean±standard deviation where applicable.

Family	Species name	East Bali			North Bali		
		Biomass (kg·ha ⁻¹)	Size (cm)	n (ind)	Biomass (kg·ha ⁻¹)	Size (cm)	n (ind)
Acanthuridae (H)	<i>Acanthurus pyroferus</i>	0.028±0.0132	8±0.5	2	0.6892±0.04	8±2	3
	<i>Acanthurus auranticavus</i>	1.124±0.047	9±1	2	41.2267±0.39	72±4.85	101
	<i>Acanthurus blochii</i>	0.561	9	1	0	0	0
	<i>Acanthurus nigricans</i>	2.425±0.71	10.75±2.6	2	0	0	0
	<i>Acanthurus lineatus</i>	1.305±1.21	7.5±3.1	4	0	0	0
	<i>Acanthurus tristis</i>	0	0	0	0.6478±1.7	13±2.7	11
	<i>Acanthurus nigroris</i>	0	0	0	2.457±0.26	31±3.2	6
	<i>Acanthurus nigrofuscus</i>	0	0	0	0.258±0.51	8±1.4	18
	<i>Acanthurus grammoptilus</i>	0	0	0	0.782±1.5	13±3.6	17
	<i>Ctenochaetus striatus</i>	23.435±2.71	23.5±5.9	26	3.0226±1.52	44±4.8	84
	<i>Zebrasoma veliferum</i>	1.064±1.01	9±1	2	0	0	0
	<i>Zebrasoma rostratum</i>	0	0	0	1.439	28	1
	<i>Zebrasoma scopas</i>	1.259±0.231	8±0.7	3	1.0248±0.98	34±1.69	19
Siganidae (H)	<i>Siganus guttatus</i>	0.067±0.11	13±1	2	0	0	0
	<i>Siganus vulpinus</i>	0.767±0.03	16±1.2	8	0	0	0
	<i>Siganus virgatus</i>	3.278±1.4	12±3	4	0.21±0.05	18±0.76	2
Scaridae (H)	<i>Chlorurus sordidus</i>	0.367±1.01	18±3.7	3	0	0	0
	<i>Chlorurus capistratoides</i>	1.871±0.97	13±1	2	0	0	0
	<i>Chlorurus bleekeri</i>	2.574±0.32	11±1	3	0	0	0
	<i>Scarus spinus</i>	0	0	0	0.103±0.27	28±1	2
	<i>Scarus tricolor</i>	0.031±0.1	8±2	4	0.979±0.71	33±1	2
	<i>Cetoscarus bicolor</i>	0	0	0	0.023±0.07	8±2	3
Haemulidae (C)	<i>Plectorhinchus vittatus</i>	1.189±1.7	33±6.1	3	0.8408±0.53	41±3.4	7
	<i>Plectorhinchus lineatus</i>	1.757±1.3	51±3.2	6	0	0	0
	<i>Plectorhinchus chaetodontoides</i>	2.299±0.7	13±2	2	0	0	0
	<i>Plectorhinchus polytaenia</i>	2.02±1.09	14±3.2	2	0	0	0
Serranidae (C)	<i>Cephalopholis argus</i>	2.3923±0.09	28±4	4	0.4525±0.31	31±1.1	7
	<i>Cephalopholis miniata</i>	0	0	0	0.079±0.12	13±1.8	2
Lutjanidae (C)	<i>Lutjanus lutjanus</i>	0	0	0	0.549±1.7	18±3	7
	<i>Lutjanus ehrenbergi</i>	0	0	0	0.689±2	33±2	3

Note: H = Herbivores; C = Carnivores; n = number of individuals.

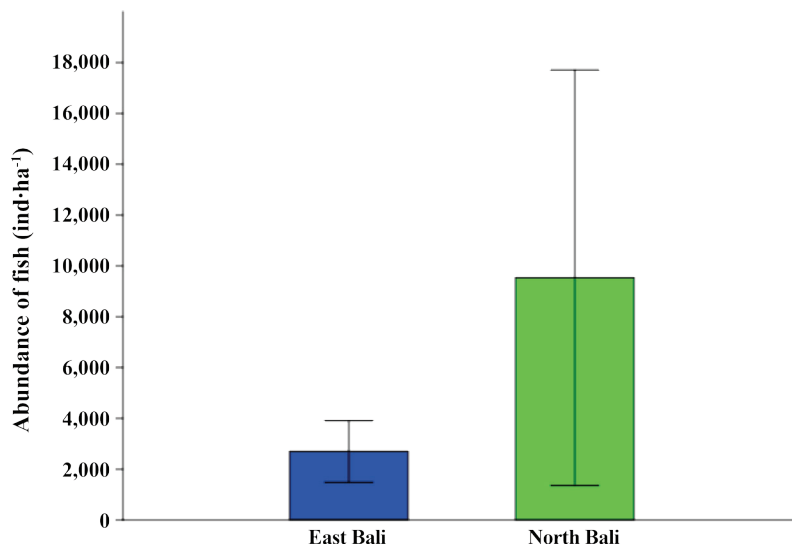


Figure 6. Mean reef fish abundance (ind·ha⁻¹) in East and North Bali. Bars represent mean values, and error bars indicate standard deviation among sites within each region.

The dominance of Acanthuridae in both East and North Bali indicates the presence of an important herbivorous component of the reef fish assemblage. These fish may contribute to grazing and the regulation of algal growth (Faricha *et al.*, 2024). However, because trophic interactions and grazing rates were not directly measured in the present study, these interpretations should be regarded as potential ecological functions rather than direct evidence of ecosystem functioning.

Acanthuridae comprises conspicuous and abundant herbivorous fishes commonly inhabiting coral reef systems across tropical and subtropical coastal environments. The abundance and biomass of acanthurids may be particularly high on reef flats, where large schools are frequently observed in shallow areas (Hernández-Landa and Aguilar-Perera, 2019). Members of Acanthuridae play a fundamental role in the functioning of coral reef ecosystems due to their capability to control macroalgae abundance (Delgado-Pech *et al.*, 2018).

Several species recorded in this study, including *Acanthurus nigricans*, *Acanthurus nigrofusus*, *Acanthurus lineatus*, and *Acanthurus pyroferus* (Table 2), are herbivores that may contribute to regulating algal growth on coral

reefs. Through grazing activity, these fishes help maintain the balance between coral and algal communities, thereby supporting reef ecosystem stability and recovery processes (Rani *et al.*, 2023).

Variation in reef fish assemblages among sites may reflect differences in habitat characteristics, environmental conditions, or anthropogenic pressures. Understanding these variations could be useful for targeted conservation efforts (Watt-Pringle *et al.*, 2024), significant ecological (Boakes *et al.* 2023) and economic roles coral reefs play (Windayati *et al.*, 2022), particularly in supporting diverse fish populations that are vital for maintaining reef health and providing livelihoods for local communities.

Coral health and ecological implications

Live coral cover and Coral Health Index (CHI) scores varied among sites. Live coral cover and Coral Health Index (CHI) scores varied among sites. Based on the stated thresholds, five sites were classified as having high recovery potential, whereas Les and Bondalem were classified as having low recovery potential because fleshy seaweed cover exceeded 3% (Table 3). Padang Bai and Blue Lagoon had low live coral cover and CHI scores of 3, whereas Jemeluk Bay had moderate

Table 3. Coral Health Index classifications based on live coral cover, recovery potential, and reef fish biomass at the seven study sites in East and North Bali.

Sites Code	Lc (%)	Coral percentage	Fs (%)	Rubble (%)	Resilience	Fish biomass (kg·ha ⁻¹)	Reef fish biomass	Coral Health Index
East Bali								
PB	13.14	Low	0.6	34.47	High	3.199	Low	3
BL	16.33	Low	1	7.67	High	0.536	Low	3
JB	28.73	Moderate	2.67	34.87	High	44.95	Low	5
North Bali								
LS	23.87	Moderate	21.27	1.33	High	7.482	Low	5
BD	38.77	High	7.51	0.14	High	3.655	Low	6
PC	16.67	Low	0.20	0.73	High	38.26	Low	3
PN	24.47	Moderate	0	0	High	6.07	Low	5

Note: PB = Padang Bai; BL = Blue Lagoon; JB = Jemeluk Bay; LS = Les; BD = Bondalem; PC = Pacung; PN = Penimbangan

live coral cover and a CHI score of 5. In North Bali, CHI scores ranged from 2 to 5 after recovery-potential categories were corrected. These values are within the range reported for Sangiang Island (Aprilian *et al.*, 2021).

These results indicate that the reefs assessed in this study still retain ecological characteristics associated with recovery potential, although variability among sites suggests differing levels of ecological condition and management needs. However, interpretation of CHI values should remain within the context of the specific framework applied in this study. Reef fish biomass was consistently low across all sites, a concerning trend given the critical role of fish in maintaining reef health.

The moderate live coral cover, consistently low reef fish biomass, and spatial variation in CHI scores observed in this study may reflect differences in local environmental conditions and anthropogenic pressures between East and North Bali. Previous studies have reported that coral reefs in these regions face significant stressors, likely from diseases (Karim, 2019), pollution (Baum *et al.*, 2015; Boakes *et al.*, 2022; Badriana *et al.*, 2024), and climate change impacts such as coral bleaching (Suparno *et al.*, 2019). Low reef fish biomass exacerbates the issue, as it impairs the natural algae control essential for coral growth and habitat stability (McManus *et al.*, 2019; Tebbett *et al.*, 2020).

However, because these stressors and ecological processes were not directly measured in the present study, they should be interpreted as plausible contextual explanations rather than confirmed causal drivers of the observed reef condition.

Variation in coral health between East and North Bali may also be associated with differences in human activity levels, natural conditions, or reef management. Previous studies of Bali's reef systems have reported that tourism, sedimentation, and climate-related disturbances can contribute to reduced live coral cover and increased degraded benthic categories (Subhan *et al.*, 2024). Similar patterns have been reported at Bangka Island, Indonesian, where reefs exposed to wastewater discharge, mining, and destructive fishing experiences increased coral stress and disease prevalence (Ponti *et al.*, 2016).

The proximity of coral reefs to villages and human settlements often correlates with higher sedimentation rates and pollution, which further degrade coral ecosystems (Aji *et al.*, 2024). Such pressures may provide context for the variation observed among the Bali study sites; however, their effects cannot be directly inferred because they were not measured. The site-level variation nevertheless reinforces the importance of management interventions that address local stressors and support reef recovery potential (Sangaji *et al.*, 2024).

Despite these challenges, five sites retained benthic conditions classified as having high recovery potential under the threshold-based CHI framework. This recovery potential should be interpreted cautiously, as direct resilience processes such as coral recruitment (Manikandan *et al.*, 2017), juvenile survival (Fisher, 2022), and long-term recovery were not measured in this study. However, reef fish biomass remained low across all sites, indicating that the fish component of reef condition is still weak and may limit ecological functions such as herbivory and trophic regulation.

To address these issues, management efforts should focus on maintaining benthic recovery potential while improving reef fish biomass through site-specific monitoring, reduction of local pressures, and protection of key herbivorous fish groups. Broader conservation actions, including restoration planning (Levy *et al.*, 2024) and community engagement (Siriwong and Trues, 2018; Bradley *et al.*, 2020), may further support reef management when guided by site-specific ecological data.

Bali's coral reefs are vital not only for marine biodiversity but also for the ecosystem services they provide, such as coastal protection and support for fisheries. The present findings emphasize the need for integrated, site-specific management to safeguard these ecosystems. Targeted management and long-term monitoring may help maintain recovery potential, improve reef condition, and sustain ecological and socioeconomic benefits.

CONCLUSION

This study provides baseline ecological information on coral reef condition and recovery potential across selected reef sites in East and North Bali using integrated indicators of benthic cover, reef fish assemblage, reef fish biomass, and threshold-based CHI classifications. Across all seven study sites, 380 reef fish individuals were recorded, including 85 individuals across three East Bali sites and 295 across four North Bali sites. Mean live coral cover was 19.40% in East Bali and 25.94% in North Bali, but the difference was not

statistically significant. No significant difference in standardized reef fish abundance was found between East and North Bali, and Acanthuridae was the dominant fish family in both regions.

Five sites retain were classified as having high recovery potential under the threshold-based CHI framework, whereas Les and Bondalem had low recovery potential because fleshy seaweed cover exceeded the stated threshold. Reef fish biomass was classified as low at all sites. These findings indicate that some reefs retain benthic characteristics associated with recovery potential, although this should not be interpreted as direct evidence of long-term ecological resilience.

Conservation efforts should focus on reducing local stressors, protecting key herbivorous fishes, strengthening community participation, and applying restoration only where supported by site-specific ecological assessments. Further research is recommended to monitor temporal trends and evaluate the effectiveness of management action in sustaining reef ecosystems and their ecological services.

ACKNOWLEDGEMENTS

The authors express their gratitude to Udayana University for the financial support provided through the research grant (B/1.628/UN14.4.A/PT.01.03/202). The authors also appreciate the contributions of field team members and local communities in East and North Bali for their cooperation during the study and help us to facilitating fieldwork and data collection. This research would not have been possible without their valuable support and collaboration.

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