Omni-Akuatika, 22 (1): 40 - 52, 2026
ISSN: 1858-3873 print / 2476-9347 online

Research Article

journal homepage: http://ojs.omniakuatika.net

Resilience Under Pressure: Application of CRes Index to Monitor Coral Ecosystem Shifts in Jaboi, Aceh Post-Mass Bleaching Events

Nadia Aldyza*, Afkar

Department of Biology Education, Faculty of Teacher Training and Education, Universitas Almuslim, Bireuen, Aceh, 24261, Indonesia.

**Corresponding author: nadia.aldyza@gmail.com*

Received 6 February 2026; Revised 26 May 2026, Accepted 20 July 2026; Available online 18 August 2026, Published 18 August 2026

ABSTRACT

This study assessed the resilience of coral reef ecosystems in the coastal waters of Jaboi, Sabang City, Weh Island, conducted in August 2025. The study area is an open marine zone that has not yet been designated as a marine protected area, highlighting the urgency of evaluating ecosystem resilience as a scientific basis for future conservation planning. Data collection was conducted using six parallel transects installed along the coastline at depths of 3 m and 7 m. Coral cover, turf algae, Crustose Coralline Algae (CCA), and rubble were recorded using 50 m line transects combined with underwater video analysis, while the density of blue sea stars (Linckia laevigata) and sea urchins was assessed using belt transects (100 m²). The results indicated that shallow waters exhibited higher live coral cover, greater CCA presence, and higher abundance of L. laevigata, reflecting a more stable ecosystem with strong recovery potential. In contrast, deeper waters showed increased dominance of turf algae and higher sea urchin density, suggesting emerging ecological pressures despite remaining within the high-resilience category. Differences in substrate quality between depths were identified as a key factor influencing benthic community structure. Overall, the coral reefs of Jaboi demonstrate relatively high resilience; however, early signs of ecological stress emphasize the need for continuous monitoring and proactive management. The findings support the use of the CRes Index as an effective tool for reef resilience assessment and provide essential baseline data to inform conservation zoning, restoration initiatives, and sustainable coastal management in Indonesia.

Keywords: Algae, Coral, Jaboi, Monitoring, Resilience

ABSTRAK

Penelitian ini bertujuan untuk menilai tingkat resiliensi ekosistem terumbu karang di perairan Jaboi, Kota Sabang, Pulau Weh, yang dilaksanakan pada bulan Agustus 2025. Lokasi penelitian merupakan wilayah perairan terbuka yang belum ditetapkan sebagai kawasan konservasi perairan, sehingga memiliki urgensi tinggi untuk dilakukan kajian resiliensi sebagai dasar ilmiah dalam perencanaan kawasan konservasi. Pengumpulan data dilakukan menggunakan enam transek sejajar garis pantai pada kedalaman 3 m dan 7 m. Data tutupan karang hidup, turf algae, Crustose Coralline Algae (CCA), dan rubble diperoleh melalui metode transek garis sepanjang 50 m yang dikombinasikan dengan analisis video bawah air, sedangkan kepadatan bintang laut biru (Linckia laevigata) dan bulu babi dikaji menggunakan metode belt transect seluas 100 m². Hasil penelitian menunjukkan bahwa zona perairan dangkal memiliki persentase tutupan karang hidup dan keberadaan CCA yang lebih tinggi, serta kelimpahan L. laevigata yang lebih besar, yang mencerminkan kondisi ekosistem yang lebih stabil dengan potensi pemulihan yang baik. Sebaliknya, pada perairan yang lebih dalam ditemukan peningkatan dominasi turf algae dan kepadatan bulu babi, yang mengindikasikan adanya tekanan ekologis awal meskipun masih berada dalam kategori resiliensi tinggi. Perbedaan kualitas substrat antar kedalaman diidentifikasi sebagai faktor penting yang memengaruhi struktur komunitas bentik. Secara keseluruhan, ekosistem terumbu karang di perairan Jaboi menunjukkan tingkat resiliensi yang relatif tinggi. Namun demikian, indikasi tekanan ekologis yang mulai muncul menegaskan pentingnya pemantauan berkelanjutan dan pengelolaan adaptif. Hasil penelitian ini memberikan data dasar yang

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penting untuk mendukung penetapan zona konservasi, kegiatan restorasi, serta pengelolaan wilayah pesisir yang berkelanjutan di Indonesia.

Kata kunci: Algae, Karang, Jaboi, Monitoring, Ketahanan

1. Introduction

Coral reefs are marine ecosystems characterized by high levels of structural and ecological complexity and provide a wide range of benefits to human societies, including serving as habitats for diverse marine biota, acting as natural coastal protection against erosion, and supporting fisheries and tourism sectors. Nevertheless, these ecosystems are increasingly threatened by the combined effects of environmental pressures and intensive human activities. In Aceh waters, particularly around Weh Island, ecological pressure on coral reefs has increased significantly following mass coral bleaching events that have been recorded since 2010. Similar phenomena have also been reported in various Indonesian waters, such as Karimunjawa , as well as on a global scale, including the Great Barrier Reef ecosystem in Australia.

Previous studies in Aceh waters indicated that more than 35% of hard coral colonies have experienced mortality, with average live coral cover declining from 3.25% in 2009 to 2.6% in 2011, followed by further decreases in subsequent periods . This pattern suggests that coral reef recovery processes are slow and highly vulnerable to additional disturbances. In addition to natural factors, such as increasing sea surface temperatures driven by global climate change, anthropogenic pressures have also contributed substantially to coral reef degradation. Destructive fishing practices using explosives , pollution and sedimentation , as well as physical disturbances including ship anchoring and poorly managed tourism activities, are among the primary factors accelerating the decline in coral reef ecosystem quality. In the context of Aceh waters, the decline to 2.6% coral cover cannot be separated from the impact of the 2010 mass bleaching event linked to elevated sea surface temperatures . However, field conditions in this region also indicate ongoing local pressures, particularly increased sediment input from coastal runoff, intensive use of nearshore reef areas for tourism and fishing activities, and physical disturbances caused by boat anchoring. These pressures can reduce water clarity, damage coral structures, and limit successful coral recruitment. Under such conditions, recovery becomes constrained, and the effects of bleaching tend to persist over time. This suggests that the observed decline is not driven by a single factor, but rather by the combined influence of thermal stress and continuous local disturbances that weaken reef resilience.

Elevated seawater temperatures induce physiological stress in coral polyps, which is characterized by the expulsion of zooxanthellae from their intracellular tissues . The loss of these symbiotic algae directly reduces the coral's capacity for photosynthesis and energy acquisition, thereby increasing the risk of mass coral mortality. If such conditions persist without appropriate mitigation and management efforts, the sustainability of coral reef ecosystems and their associated ecological and economic functions will be increasingly threatened. Therefore, a comprehensive understanding of coral reef degradation dynamics and recovery potential is urgently needed, particularly in Aceh waters, including the Jaboi waters.

Jaboi waters exhibit a high level of coral reef vulnerability due to repeated bleaching events associated with major thermal anomalies recorded in Indonesian waters in 2010 and 2015–2016, with continued post-bleaching ecological degradation observed in recent years . These events have resulted in significant declines in coral cover and alterations in coral community structure. Branching genera such as Acropora and Pocillopora, which play a crucial role in providing structural complexity in habitat, have experienced sharp population declines. In contrast, the current coral community is dominated by Massive and Submassive growth forms, such as Porites, which are known to exhibit higher tolerance to environmental stressors.

This shift in dominance reflects a transition in coral community composition toward species that are more tolerant of thermal stress and anthropogenic pressures, albeit with lower structural complexity. reported that post-bleaching recovery of Acropora in several Indonesian regions has been extremely slow due to low larval recruitment rates and intense spatial competition. These findings are consistent with observations in Jaboi waters, where coral cover is approximately 40% and the Shannon–Wiener diversity index is 1.42, indicating a moderate but stagnant ecosystem condition . This condition suggests that the potential for natural coral reef recovery in the Jaboi waters is relatively limited in the absence of ecologically based management interventions and long-term monitoring.

To date, coral reef monitoring in Jaboi waters has primarily focused on hard coral cover parameters, despite the fact that coral bleaching impacts extend beyond coral mortality to include changes in benthic substrate composition, reduced recruitment of new coral colonies, and shifts in community dominance from corals to algae. These changes result in declines in ecosystem functioning, including reduced habitat availability for associated biota and decreased fisheries productivity. Long-term monitoring data from Weh Island indicate that coral cover continues to decline even after bleaching episodes have subsided, suggesting that ecosystem recovery processes are slow and unstable. Repeated bleaching events combined with increasing anthropogenic pressures place coral reef ecosystems in Jaboi under persistent stress, highlighting the importance of resilience-based assessments to better understand ecosystem responses and community shifts.Previous studies have also reported the occurrence of coral reef degradation and disease in several locations within Weh Island waters, further indicating that reef ecosystems in this region are exposed to multiple and persistent stressors.

Based on these limitations, the novelty of this study lies in the application of the Coral Resilience Index (CRes Index) to evaluate coral reef conditions in Jaboi waters following repeated bleaching events while considering differences across depth gradients. Unlike previous studies in Weh Island that primarily focused on hard coral cover or individual indicators, this study incorporates benthic indicators, bioindicators, and substrate characteristics to assess reef resilience. This approach provides additional ecological information on changes in community structure and habitat condition that may not be captured by coral cover assessment.

In this context, the application of the Coral Resilience Index (CRes Index) represents a relevant and comprehensive approach for assessing coral reef conditions. The index integrates several ecological indicators related to benthic condition, substrate stability, and reef-associated megabenthic organisms to evaluate ecosystem recovery potential following disturbance events. The selection of indicators was based on a previous statistical modeling approach developed for coral reef ecosystems in Weh Island. The application of the CRes Index in Jaboi waters is expected to generate robust scientific information to support ecosystem-based coral reef management. This approach aligns with national policies, including Law No. 1 of 2014 on the Management of Coastal Areas and Small Islands and the Minister of Environment Decree No. 4 of 2001 concerning criteria for coral reef damage. Therefore, this study aims to assess coral reef resilience levels and identify key factors influencing ecosystem dynamics and shifts in coral reef communities in Jaboi waters through the application of the CRes Index.

2. Materials and methods

This study was conducted in August 2025 in the waters of Jaboi, Sabang City, Weh Island. The study area is an open-access marine zone that has not yet been designated as a marine protected area, thus presenting a high level of urgency for assessing coral reef ecosystem resilience. Data obtained from this study are expected to serve as a scientific basis for the establishment of new conservation zones and to support the implementation of coral restoration or transplantation programs aimed at maintaining the sustainability of coastal ecosystems. Conservation is a strategic approach for improving and maintaining marine environmental quality, which is increasingly under pressure from anthropogenic activities (Ampou et al., 2024; Forsblom et al., 2024). Data collection was carried out at six transect stations installed parallel to the coastline to obtain a representative overview of coral reef conditions. Observations were conducted within the coordinate range of 95°20′45.776″E and 5°47′59.204″N to 95°20′53.48″E and 5°48′11.447″N, encompassing areas with ecologically important characteristics and significant potential environmental disturbances.

2.1 Development and Ecological Basis of the CRes Index

The ecological indicators used in the CRes Index were selected based on a previous stepwise multiple regression analysis conducted in coral reef ecosystems around Weh Island. Six variables were identified as the most influential predictors in assessing coral reef resilience, namely live coral cover, turf algae, Crustose Coralline Algae (CCA), rubble substrate, *Diadema* spp., and *Linckia* spp. The inclusion of these variables progressively increased the explanatory power of the regression model up to R^2 = 83.2%, indicating strong statistical performance in explaining variations in coral reef resilience.

Ecologically, live coral cover represents the structural integrity of coral reef ecosystems, while CCA reflects substrate stability and coral recruitment potential. Turf algae and rubble substrate were included as indicators of ecological stress and post-disturbance habitat degradation. *Diadema* spp. were incorporated because of their role as herbivorous grazers that help control algal overgrowth and support coral recruitment processes (Do Hung Dang et al., 2020; Fong et al., 2024). Meanwhile, *Linckia* spp. were included as supporting megabenthic bioindicators associated with stable coral-dominated habitats and structurally complex reef environments (Gaffar et al., 2014; Otwoma & Kochzius, 2016; Waheed et al., 2023). The stepwise regression model used for selecting the indicators is presented in Table 1.

2.2 Percentage Cover of Coral, Turf Algae, CCA, and Rubble

Data on coral cover, turf algae, Crustose Coralline Algae (CCA), and rubble were collected using a 50-m line transect method, deployed at six stations parallel to the shoreline. The transect line was positioned on the left side of the diver to ensure consistency in observation direction. Benthic biota observations were conducted using underwater video techniques (Mutaqin et al., 2020) combined with direct in situ field recording. Each point along the transect over coral substrates was analyzed to identify benthic components, observe growth forms (life forms), and calculate the percentage cover of each benthic category. This approach enables a systematic and accurate quantitative evaluation of coral reef ecosystem conditions and supports ecological interpretation relevant to coastal conservation and management objectives.

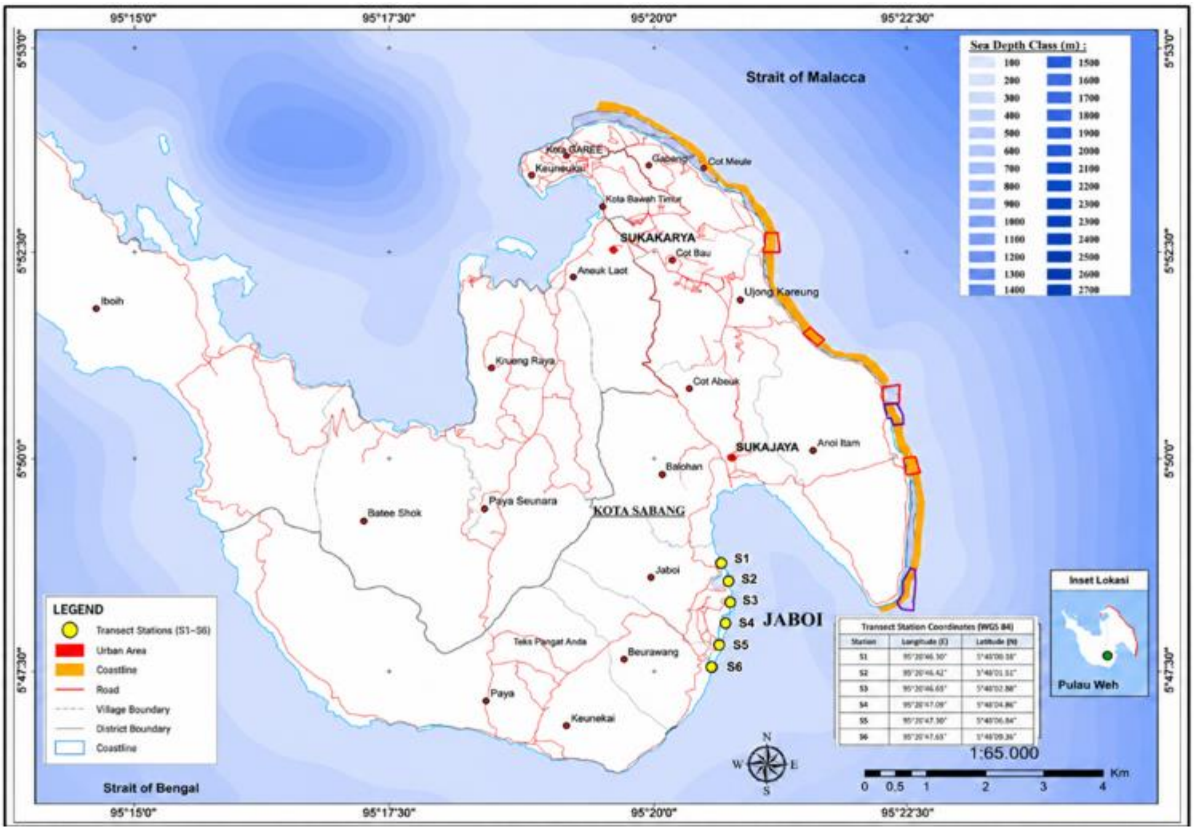

Figure 1. Research Map

Table 1. Stepwise multiple regression models used to develop the CRes Index and the contribution of selected ecological indicators to model explanatory power (R^2)

No.	Regression Equations	R^2
1.	$Y = 38.65 – 0.40X_4$	18.5%
2.	$Y = 51.79 – 0.55X_4 – 0.63X_7$	38.7%
3.	$Y = 47.13 – 0.65X_4 – 0.74X_7 + 2.71X_5$	58.8%
4.	$Y = 57.31 – 0.77X_4 – 0.90X_7 + 3.18X_5 – 3.51X_6$	71.9%
5.	$Y = 65.39 – 0.75X_4 – 0.78X_7 + 3.26X_5 – 3.76X_6 – 128.77X_1$	82.7%
6.	$Y = 65.72 – 0.78X_4 – 0.80X_7 + 3.32X_5 – 3.72X_6 – 139.74X_1 + 22.02X_2$	83.2%

Note: X1 = Sea urchin (*Diadema* spp.); X2 = Blue sea star (*Linckia* spp.); X3 = Giant clam; X4 = Turf algae; X5 = Crustose Coralline Algae (CCA); X6 = Seaweed; and X7 = Rubble substrate.

2.3 Percentage Cover of Coral, Turf Algae, CCA, and Rubble

Data on coral cover, turf algae, Crustose Coralline Algae (CCA), and rubble were collected using a 50-m line transect method, deployed at six stations parallel to the shoreline. The transect line was positioned on the left side of the diver to ensure consistency in observation direction. Benthic biota observations were conducted using underwater video techniques (Mutaqin et al., 2020) combined with direct in situ field recording. Each point along the transect over coral substrates was analyzed to identify benthic components, observe growth forms (life forms), and calculate the percentage cover of each benthic category. This approach enables a systematic and accurate quantitative evaluation of coral reef ecosystem conditions and supports ecological interpretation relevant to coastal conservation and management objectives.

2.4 Density of Blue Sea Stars and Sea Urchins

Data on blue sea stars and sea urchins were collected using the belt transect method (Muzaki et al., 2019; Suprapto et al., 2023), with a transect length of 50 m and a width of 2 m, resulting in an observation area of 100 m² per transect (Figure 2). Megabenthic observations were conducted through direct field recording and documentation using underwater video techniques. Each individual blue sea star and sea urchin encountered within the observation area was counted, and their density was recorded. Therefore, in addition to measuring ecological indicators using the CRes Index, this study also included observations of coral health disturbances as supporting data for ecosystem condition analysis and the formulation of coral reef management recommendations. All statistical analyses were performed using R software version 4.5.0. Data normality was evaluated using the Shapiro–Wilk test, followed by Welch's independent sample t-test to compare ecological indicators between depth strata. Statistical significance was determined at $p < 0.05$.

3. Results and Discussion

The benthic composition of Jaboi waters comprised hard corals (HC), Crustose Coralline Algae (CCA), turf algae (TA), rubble (R), as well as associated macrofauna, including blue sea stars (*Linckia laevigata*; L) and sea urchins (*Diadema* spp.; SU). Table 2 summarizes the mean values (± SD) of benthic cover and macrofaunal density recorded at two depth strata (3 m and 7 m), providing a quantitative description of substrate structure and associated fauna relevant to coral reef condition and resilience at the study site.

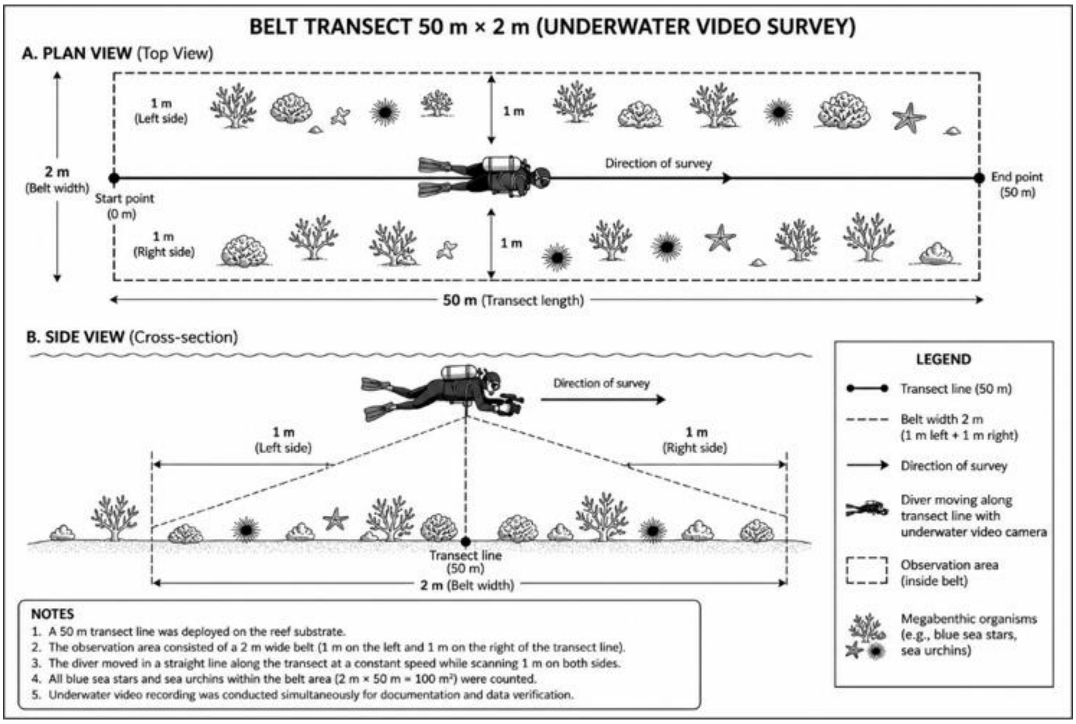

Figure 2. Schematic of the 50 m × 2 m belt transect used to survey megabenthic organisms, with observations conducted within 1 m on each side of the transect line.

Table 2. Mean (± SD) of benthic cover components (%) and macrofaunal density (ind/100 m²) at two depth strata (3 m and 7 m) in Jaboi waters.

Variable	3 m Mean ± SD	7 m Mean ± SD
Hard Coral (HC)	59.83 ± 10.25	51.83 ± 5.53
Crustose Coralline Algae (CCA)	14.00 ± 4.60	15.83 ± 4.22
Linckia laevigata (L)	4.17 ± 1.17	2.83 ± 0.75
Turf Algae (TA)	9.67 ± 4.32	15.33 ± 8.59
Sea Urchins (SU)	4.00 ± 1.41	4.50 ± 1.05
Rubble (R)	10.33 ± 4.08	9.33 ± 2.80

**HC = Hard Coral; CCA = Crustose Coralline Algae; TA = Turf Algae; R = Rubble; L = Linckia; SU = Sea Urchins*.

The mean cover (± SD) of benthic components and the mean density of key macrofauna across two depth strata are summarized in Table 1, providing an overview of habitat structure and reef condition in Jaboi waters. At 3 m depth, the reef was dominated by live coral, with an average cover of 59.83 ± 10.24%, indicating a structurally intact shallow reef environment. This condition was accompanied by moderate Crustose Coralline Algae (CCA; 14.00 ± 4.60%) and relatively low Turf Algae (TA; 9.66 ± 4.32%) and unconsolidated substrates, suggesting limited space competition and low levels of ecological disturbance. Similar benthic configurations have been reported from other reef systems around Weh Island, where variation in coral cover and associated benthic components reflects differences in reef condition and resilience across sites (Aldyza et al, 2022a; Aldyza, et al., 2022b).The predominance of consolidated hard substrates at 3 m depth supports favorable conditions for reef-associated macrofauna. The higher mean density of the blue sea star *Linckia laevigata* (4.16 ± 1.17 individuals per 100 m²) in the shallow zone is consistent with the species' known association with coral-dominated habitats (Figure 3a). Previous studies have demonstrated that L. *laevigata* preferentially occupies reef areas characterized by high structural complexity, which provide stable surfaces for movement as well as shelter and feeding opportunities (Gaffar et al., 2014; Otwoma & Kochzius, 2016). Findings from Weh Island further indicate that areas with higher coral cover tend to support greater abundances of reef-associated fauna, reinforcing the patterns observed in Jaboi waters (Aldyza et al., 2022b).

Crustose coralline algae represents a key indicator of habitat quality within the shallow reef. Although it does not constitute a direct food source for *Linckia*, its presence reflects stable substrates, low sediment accumulation, and environmental conditions conducive to calcifying organisms (Figure 3c). Rothstein et al. (2025) showed that CCA is prevalent in stable reef microhabitats and contributes significantly to carbonate production, while Tâmega & Figueiredo. (2019) emphasized its high colonization capacity under favorable environmental conditions. Moreover, Weiss & Martindale. (2017) and Tsikopoulou et al. (2021) highlighted the role of CCA in reinforcing reef framework development and maintaining long-term benthic community stability. Accordingly, the relatively high CCA cover observed at 3 m depth indicates habitat conditions that are particularly suitable for hard substrate-dependent fauna such as L. *laevigata*.

In contrast, reef condition at 7 m depth exhibited a clear shift in benthic composition. Mean live coral cover declined to 51.83 ± 5.53%, while TA increased to 15.33 ± 8.59%, accompanied by higher sand and rubble cover. Increased dominance of TA is widely interpreted as an early signal of ecological stress, often linked to reduced substrate consolidation or increased sediment influence (Figure 3d), which can intensify competition for space on reef surfaces. Although CCA cover remained relatively high (15.83 ± 4.22%), the concurrent increase in TA and unconsolidated substrates indicates a decline in overall substrate quality compared to the shallow zone.

These changes in benthic structure were reflected in macrofaunal distribution patterns. The mean density of L. *laevigata* decreased to 2.83 ± 0.75 individuals per 100 m² at 7 m depth, suggesting reduced habitat suitability for this species. Turf algae can overgrow dead coral surfaces, limiting access to consolidated substrates and reducing habitat complexity, thereby constraining movement and shelter availability for *Linckia* spp.. Similar patterns have been reported from Indo-Pacific reefs, where *Linckia* spp. is less frequently observed in areas dominated by TA and unconsolidated substrates (Tebbett & Bellwood, 2020).

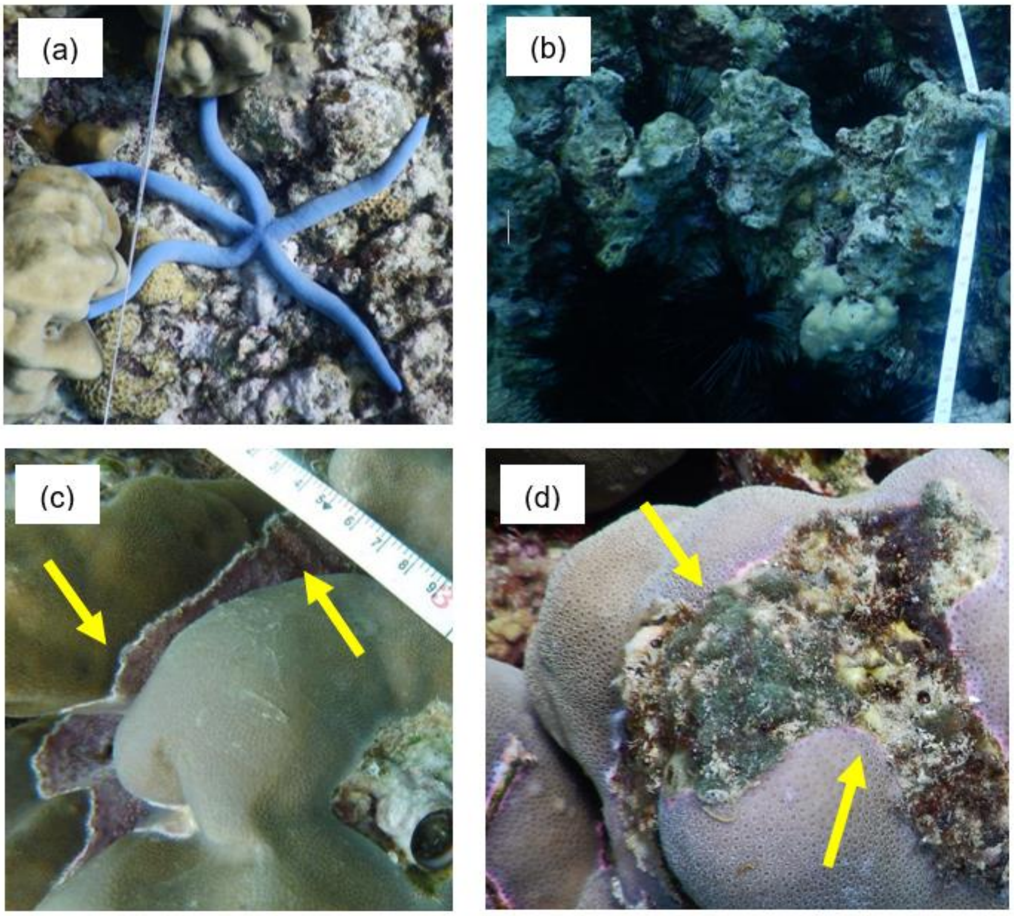

Figure 3. Benthic components and associated macrofauna observed in Jaboi waters: (a) blue sea star *L. laevigata* on consolidated coral substrate; (b) Sea urchin *Diadema* spp. occupying crevices of exposed dead coral substrate.; (c) Crustose Coralline Algae (CCA) encrusting exposed dead areas near massive Porites colonies; and (d) turf algae covering reef substrate.

Table 3. Results of the Shapiro–Wilk normality test and Welch's independent sample t-test for ecological indicators included in the CRes Index between 3 m and 7 m depth strata in Jaboi waters.

Variable	Shapiro-Wilk_(3m)	Shapiro-Wilk_(7m)	t_value	p_value
Hard Coral	0.533	0.339	1.683	0.132
Turf Algae	0.698	0.282	-1.443	0.190
Linckia laevigata	0.421	0.212	2.349	0.045
CCA	0.368	0.910	-0.719	0.488
Sea Urchins	0.960	0.820	-0.696	0.504
Rubble	0.926	0.111	0.495	0.633

Conversely, sea urchins (*Diadema* spp.) displayed an opposite depth-related trend, with mean densities increasing from 4.00 ± 1.41 individuals per 100 m² at 3 m to 4.50 ± 1.05 individuals per 100 m² at 7 m depth. This increase corresponded with higher rubble and sand cover, which commonly provide shelter and foraging opportunities for *Diadema* spp. (Figure 3b). (Vimono et al., 2023) reported that *Diadema* spp. frequently attains higher densities in sandy and rubble-dominated habitats, where crevices and unstable substrates facilitate predator avoidance. Supporting this interpretation, de Breuyn et al. (2023) and Tuohy et al. (2020) demonstrated that fragmented substrates and physical refugia play a critical role in the survival and persistence of *Diadema* populations.Overall, the observed patterns indicate that shallow reef zones in Jaboi waters provide more favorable habitat conditions for hard substrate-associated fauna such as *Linckia laevigata*, while deeper zones show early indications of substrate degradation that favor more substrate-tolerant organisms such as *Diadema* spp.. These findings are consistent with international literature and underscore the importance of benthic substrate composition as a key driver of macrofaunal distribution and coral reef resilience.

Prior to comparative analysis, all variables were subjected to the Shapiro–Wilk normality test. The results indicated that all ecological indicators at both depth strata were normally distributed ($p > 0.05$), thereby meeting the assumptions required for further analysis using an independent sample t-test. The comparison between 3 m and 7 m depths showed that only the abundance of *Linckia laevigata* differed significantly between depths ($t = 2.349$; $p = 0.045$), with higher abundance recorded in shallow reef areas. In contrast, no significant differences were observed in hard coral cover, turf algae, Crustose Coralline Algae (CCA), sea urchins, rubble, or sand substrate ($p > 0.05$).

Although most benthic indicators did not differ significantly between depths, the CRes Index showed noticeable variation in resilience characteristics between the two reef zones. At 3 m depth, the reef ecosystem was categorized as having high resilience, supported by high values of hard coral cover, CCA, sea stars, and sea urchins, while turf algae remained in the low category and rubble was classified as moderate. At 7 m depth, the reef ecosystem also remained within the high resilience category; however, turf algae shifted to the moderate category, whereas rubble was categorized as low, suggesting the occurrence of early ecological stress and reduced substrate stability in deeper areas.

The significant difference in the abundance of *Linckia laevigata* supports the ecological interpretation generated by the CRes Index. The higher abundance of this species in shallow reefs indicates more stable and consolidated substrates, conditions that are commonly associated with healthier reef habitats and greater recovery potential. In contrast, the lower abundance recorded at 7 m depth may reflect less stable habitat conditions associated with increased turf algae dominance and fragmented substrate composition. These results indicate that the CRes Index is able to capture ecological changes in reef condition that are not always evident from conventional statistical analysis of benthic cover.

3.1. Coral Reef Resilience in Jaboi waters: Coral Condition at 3 m Depth

To assess coral reef resilience in the shallow reef zone, an index-based approach was applied using the CRes Index, which integrates benthic and biotic indicators relevant to reef condition. This approach allows an integrated interpretation of ecosystem stability and recovery potential. The resilience outcome for the 3 m depth stratum is presented in Figure 4.

Based on analysis using the CRes Index application, coral reef ecosystem resilience at 3 m depth was classified as **“High”**. This assessment aligns with resilience-based evaluation frameworks emphasizing the integration of ecological indicators, as described by Burt et al. (2025), who highlighted that combined biotic and abiotic indicators provide a comprehensive depiction of reef recovery capacity. High live coral and CCA cover at this depth indicate stable hard substrates that support benthic organism growth. This finding is consistent with Tuhumena et al. (2024) and Ceccarelli et al. (2020), who demonstrated that CCA presence and substrate stability are critical for enhancing coral recruitment success and ecosystem recovery, particularly in shallow zones that are inherently more resilient.

The presence of *Linckia laevigata* as the dominant sea star further indicates sufficient microhabitat complexity, consistent with Waheed et al. (2023), who emphasized the role of *Linckia* as an indicator of healthy coral reef ecosystems. Low turf algae cover at 3 m depth suggests minimal ecological stress, such as sedimentation or eutrophication. This observation aligns with Harvey et al. (2021), who noted that turf algae dynamics are strongly influenced by substrate and sedimentation processes, making low TA dominance a key signal of ecosystem stability. Additionally, Fong et al. (2024) reported that grazing control of turf algae by herbivores, including sea urchins, contributes significantly to reef resilience. Although *Diadema* spp. abundance was relatively high, it remained within ecologically acceptable thresholds and contributed to algal control, as demonstrated by Do Hung Dang et al. (2020), who highlighted the role of *Diadema* spp. in suppressing algal dominance and facilitating coral recruitment.

Moderate rubble cover reflects the presence of partially unstable substrate fragments without dominance. This observation aligns with Leung et al. (2025), who emphasized that rubble stabilization is a key determinant of post-disturbance reef recovery trajectories, particularly through interactions with grazing organisms such as sea urchins. Overall, the integration of ecological indicators at 3 m depth demonstrates that the ecosystem retains a strong recovery capacity, supporting the sustainability of shallow reef ecological functions, as also emphasized by McLeod et al. (2021) and Souter et al. (2021) within coral reef resilience assessment frameworks.

3.2. Coral Reef Resilience in Jaboi waters: Coral Condition at 7 m Depth

A comparison of coral reef ecosystem resilience levels in Jaboi waters at depths of 3 m and 7 m reveals ecologically meaningful differences relevant to coral reef management. The shallow-water zone exhibits relatively more stable conditions, as indicated by higher percentages of live coral cover, the presence of CCA, and greater abundance of blue sea stars (*Linckia laevigata*). These characteristics indicate a healthy ecosystem with adequate recovery capacity.

In contrast, although the deeper-water zone remains classified within the high resilience category, early indications of ecological stress are evident, particularly through increased dominance of turf algae and higher sea urchin abundance. This pattern suggests depth-related differences in substrate quality that may influence benthic community dynamics and therefore warrant close attention through continuous monitoring.

The findings of this study are consistent with those of Chou & Huang (2020), who emphasized the importance of incorporating benthic indicators in resilience-based assessments of coral reef recovery capacity. The occurrence of *Linckia laevigata* in shallow reef zones further supports its association with stable coral reef habitats, as also reported by Waheed et al. (2023), who documented strong habitat associations of the species with structurally intact reef environments across the Indo-Pacific region. Although *Linckia* spp. are not direct reef-building organisms, their presence is commonly associated with stable benthic substrates and balanced reef microhabitats. As benthic detritivores and surface grazers, they may contribute indirectly to maintaining ecological balance within coral reef ecosystems through the recycling of organic material on reef surfaces. Moreover, the increased abundance of sea urchins in deeper zones aligns with the findings of Vimono et al. (2023), who demonstrated that *Diadema* spp. exhibits a preference for sandy and rubble-dominated substrates and plays a key role in algal control and the facilitation of coral recruitment processes.

Based on these findings, several management recommendations can be proposed: (1) strengthening periodic coral reef resilience monitoring programs using the CRes Index to detect ecosystem condition changes across depth gradients; (2) designating shallow-water zones with high live coral and CCA cover as priority conservation areas; (3) controlling sources of ecological stress, such as sedimentation and eutrophication, through the regulation of coastal activities; and (4) enhancing local community involvement in reef rehabilitation and environmental education initiatives to support sustainable coral reef management. These efforts are expected to safeguard the persistence of coral reef ecosystems in Jaboi waters and contribute to the broader framework of coastal zone management in Indonesia.


CRes Index
(Coral Resilience Index)

Status Category

Indicator	Status
Hard Coral	High
Crustose Coralline Algae	High
Sea Stars	High
Turf Algae	Low
Sea Urchin	High
Rubble	Moderate

Resilience Result

High

Figure 4. Coral reef resilience condition based on the CRes Index at 3 m depth.


CRes Index
(Coral Resilience Index)

Status Category

Indicator	Status
Hard Coral	High
Crustose Coralline Algae	High
Sea Stars	High
Turf Algae	Moderate
Sea Urchin	High
Rubble	Low

Resilience Result

High

Figure 5. Coral reef resilience condition based on the CRes Index at 7 m depth

The present study provides baseline ecological information on coral reef resilience in Jaboi waters and demonstrates the applicability of the CRes Index for resilience assessment. Future monitoring efforts incorporating additional environmental variables and repeated observations would further enhance understanding of reef ecosystem dynamics and recovery processes.

4. Conclusion

This study indicates that coral reef ecosystems in Jaboi waters generally exhibit **high resilience**, as demonstrated by the integrated assessment using the Coral Resilience Index (CRes Index). However, clear depth-related differences in ecological condition were observed. Shallow reefs at 3 m depth showed greater stability, characterized by higher live coral and Crustose Coralline Algae (CCA) cover, lower turf algae dominance, and higher abundance of *Linckia laevigata*, reflecting favorable substrate conditions and strong recovery potential. In contrast, reefs at 7 m depth, although still categorized as highly resilient, displayed early signs of ecological stress, including increased turf algae and sea urchin (*Diadema* spp.) abundance, along with reduced coral cover. These patterns suggest declining substrate quality and potential constraints on long-term recovery at greater depths.

The application of the CRes Index effectively captured multidimensional aspects of reef condition beyond coral cover alone, providing early warning signals of ecosystem change. These findings highlight the importance of resilience-based assessments for ecosystem-based management, emphasizing the need to prioritize shallow reef conservation and implement continuous monitoring and stress mitigation strategies to ensure the long-term sustainability of coral reef ecosystems in Jaboi waters.

Acknowledgements

The authors gratefully acknowledge Universitas Almuslim for providing financial support for this research. We also extend our sincere appreciation to the *Panglima Laot Lhok* and the field team for their valuable assistance and support during field data collection. Their contributions were essential to the successful completion of this research.

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