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Macroinvertebrate Diversity and Tourism Impacts in Coral Reef Ecosystems: Comparative Analysis and Sustainable Management Implications from Tabuhan Island and Bangsring Underwater Beach, Indonesia

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ABSTRACT

Understanding the effects of tourism pressure on macroinvertebrate diversity is essential for sustainable coral reef management. This study compared the community structure of macroinvertebrates in two coral reef ecosystems in East Java, Indonesia—Tabuhan Island and Bangsring Underwater Beach—using the Reef Check method along 100-meter transects at three stations in each site. Tabuhan Island supported six out of nine indicator species, with diversity index (H') values ranging from 0.66 to 1.14, evenness (E) up to 0.90, and dominance (C) between 0.39 and 0.63. In contrast, Bangsring Underwater Beach exhibited a sharp decline, recording only one indicator species, with both diversity and evenness indices at zero and dominance at 1.00. Although water quality parameters in both locations met optimal standards for coral reefs, the drastic difference in macroinvertebrate community structure was strongly associated with the intensity of tourism activities, including visitor numbers exceeding 1.1 million in Bangsring over three years. These findings highlight that anthropogenic pressures, particularly from tourism, outweigh abiotic factors in shaping macroinvertebrate assemblages and reef resilience. The study recommends strict visitor regulations, spatial zoning of tourism, community engagement in monitoring, and habitat restoration to safeguard coral reef biodiversity. This research provides vital baseline data to inform sustainable management strategies and supports the achievement of Sustainable Development Goals, especially SDG 14 (Life Below Water) and SDG 12 (Responsible Consumption and Production), offering a replicable model for similar high-pressure coastal tourism regions.

1. INTRODUCTION

Macroinvertebrates, a diverse group including insects, crustaceans, molluscs, and worms, play a vital role in aquatic ecosystems. They are fundamental to maintaining ecological balance through nutrient cycling, organic matter decomposition, and by serving as an essential food source for higher trophic levels. Their involvement in nutrient recycling not only sustains ecosystem productivity but also contributes significantly to the self-purification processes of aquatic environments [1]. By breaking down organic material, macroinvertebrates facilitate the release of nutrients crucial for primary producers, such as algae and seagrasses, thereby supporting the entire food web.

Macroinvertebrates also function as valuable bioindicators of ecosystem health. Their abundance, diversity, and community composition provide insights into local environmental conditions, as these organisms are highly sensitive to pollution, habitat degradation, and environmental changes [2]. The relatively sedentary nature and multi-stage life cycles of many macroinvertebrate species further strengthen their utility as indicators; they cannot easily escape deteriorating conditions, making their presence or absence a reliable signal of local environmental quality [3, 4]. Their highly sensitive responses to pollutants and habitat change therefore provide a clearer picture of the cumulative impacts of these stressors over time [5]. Their highly sensitive responses to pollutants and habitat alteration reveal the cumulative impacts of stressors, offering both immediate and long-term perspectives on ecosystem status.

In marine environments, macroinvertebrates are commonly found in coral reef and seagrass substrates, which provide complex structures and resources necessary for their survival. Coral reefs, often described as the "rainforests of the sea," harbor some of the world's highest levels of biodiversity and offer critical services, including habitat and food, for a broad spectrum of marine life [5]. The health and presence of macroinvertebrate communities are tightly linked to the condition of these ecosystems, making them integral to coral reef stability and resilience [6]. Similarly, in seagrass meadows, macroinvertebrates are primary drivers of nutrient cycling and organic matter processing, further contributing to ecosystem functioning and resilience [7].

Indonesia, situated at the heart of the Coral Triangle, is recognized as a global biodiversity hotspot with extensive coral reef and seagrass ecosystems. These coastal habitats, especially in regions such as Southeast Asia, Australia, and the Pacific Islands, are not only ecologically significant but also underpin local economies through fisheries and marine tourism [8, 9]. The coastal waters of Bangsring and Tabuhan Island in Banyuwangi, East Java, exemplify such biodiverse systems, boasting dense coral reef cover and rich macroinvertebrate assemblages. Both areas have emerged as important destinations for marine ecotourism, attracting numerous visitors and contributing to local livelihoods while also raising public awareness of marine conservation.

However, the growing intensity of human activities—including tourism, boat traffic, and associated pollution—poses increasing threats to these ecosystems, risking the integrity of coral reefs and the health of their associated biota [10]. Physical disturbances and water quality degradation from anthropogenic pressures can profoundly alter macroinvertebrate community structures, reduce biodiversity, and compromise the resilience of coral reef systems. However, the direct impacts of intensive tourism on macroinvertebrate community structure in coral reef ecosystems remain underexplored in Indonesia, particularly through comparative analysis across high and low tourism pressure sites.

This study aims to address these concerns by comparing the structure of macroinvertebrate communities in the coral reef ecosystems of Tabuhan Island and Bangsring Underwater Beach. By analyzing the differences in community attributes, this research identifies the key environmental and anthropogenic factors shaping these variations. The findings provide baseline data that are essential for the formulation of sustainable management policies in high-pressure coastal tourism areas, and offer practical recommendations for the conservation of coral reef biodiversity.

Importantly, the outcomes of this research directly support the United Nations Sustainable Development Goals, particularly SDG 14 (Life Below Water) by advancing marine biodiversity conservation, and SDG 12 (Responsible Consumption and Production) by informing the development of responsible tourism and sustainable coastal management strategies. Furthermore, the management framework proposed herein presents a model that can be replicated in other Indonesian and Southeast Asian coastal regions facing similar challenges, thereby strengthening regional and national efforts toward sustainable development and marine ecosystem resilience.

2. MATERIAL AND METHOD

2.1 Study area

Data collection was conducted in July 2023 at two sites in Banyuwangi, East Java: Tabuhan Island Marine Tourism Park and Bangsring Underwater, Bangsring Village, Wongsorejo District (Figure 1).

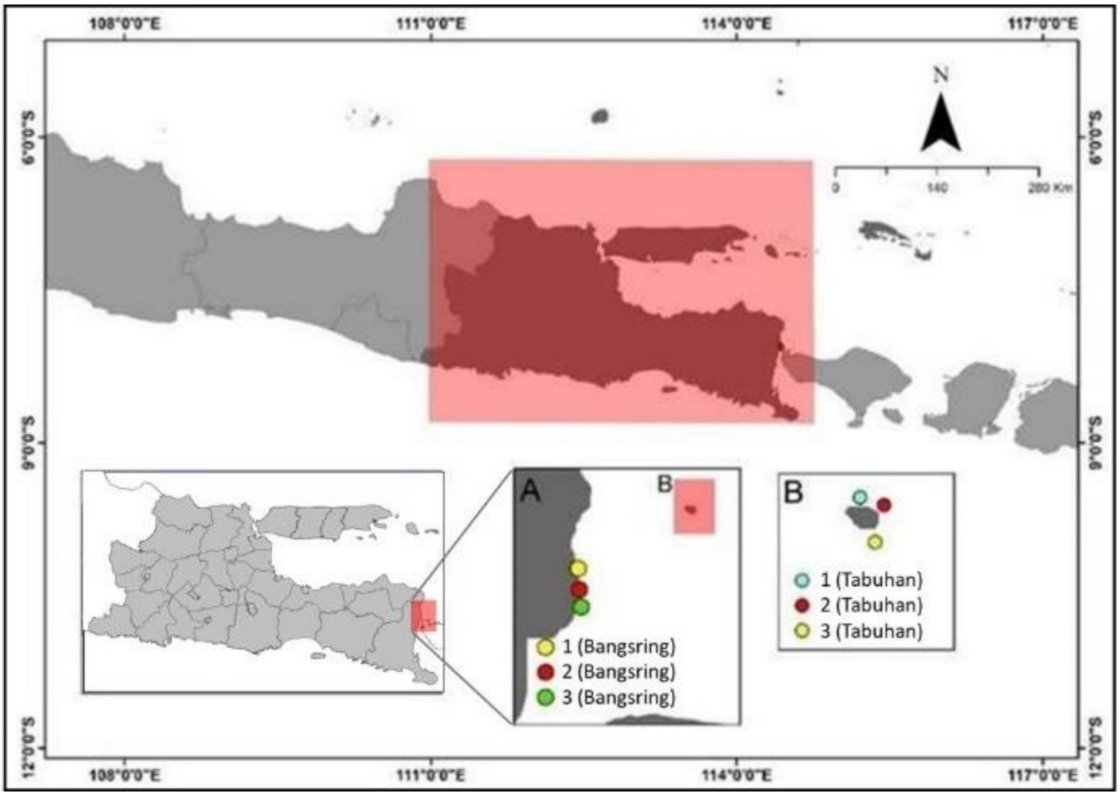


Figure 1. Research location

This study focused on Reef Check macro-invertebrate indicator taxa selected for their ecological or economic value, sensitivity to human pressure, and field identifiability. Examples include aquarium-trade species such as the banded coral shrimp Stenopus hispidus, whose depletion can indicate exploitation. Counts were made only for the macro-invertebrate indicator set; fishes and benthic plants were not surveyed in this work.

At each site, three stations were established to span the dominant substrate. Each station comprised a 100-m belt transect surveyed along a line transect. Following Reef Check practice for macro-invertebrate surveys, we enumerated indicator taxa within a 5-m line transect (2.5 m on each side of the tape) while swimming directly above the line. For reporting and internal quality control, the 100 m belt was conceptualized as 20 contiguous 5 m segments, allowing station-level and segment-level summaries (Figure 2). A single trained observer conducted all counts to minimize inter-observer bias, and voucher photos/videos were taken to validate species identification and reconcile uncertain records. Stations were positioned at accessible reef sections within the permitted survey area based on a brief on-site reconnaissance for practical reasons (access, safety, visibility); no formal habitat stratification was implemented.

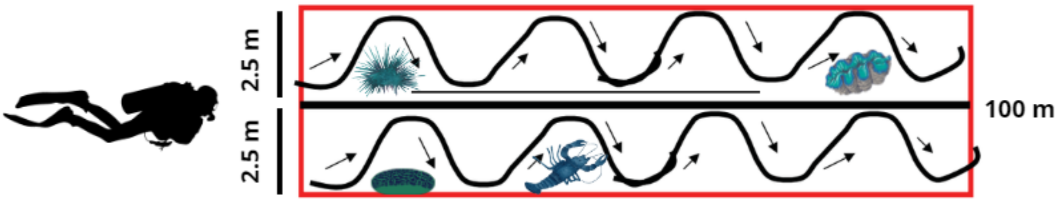


Figure 2. Macroinvertebrate illustration data collection

Table 1. Criteria for community structure index

H'	Value	E	Value	C	Value
H' < 1.0	Low	0.00–0.50	Low	0.00–0.50	Low
1.0 – 3.0	Moderate	0.50–0.75	Moderate	0.50–0.75	Moderate
H' > 3.0	High	0.75–1.00	High	0.75–1.00	High

2.2 Data analysis

The data that has been obtained is then recorded and further analyzed using Excel to obtain macroinvertebrate community structure – diversity, uniformity, dominance (Table 1): The diversity index (H') was used according to the Shannon–Wiener diversity index [11].

$$H' = -\sum_{i=1}^{s} (pi)(\ln pi) \quad (1)$$

Description:
pi: the proportion of the number of Ith individuals to individuals of all species
H': species diversity index
Ni: number of individuals of a species
N: number of individuals of all species

The Evenness Index (E) was calculated using the following guidelines [11], with the following formula:

$$E = \frac{H'}{H\max} \quad (2)$$

Description:
E: Evenness index
H': Shannon–Wiener diversity index
H max: ln S
s: Number of species

The Dominance index (C) was calculated using Simpson's dominance index [12], with the following formula:

$$C = \sum \left(\frac{ni}{N}\right)^2 \quad (3)$$

Description:
C: Dominance index
ni: Number of individuals of each species
N: Number of individuals of all species

Water quality (dissolved oxygen, temperature, salinity, pH, and depth) was measured in situ with a multiparameter sonde (AAQ-RINKO 1183S-F; JFE Advantech, Japan) equipped with a fast-response optical DO sensor (T63 = 0.4 s). Current speed was measured with a Flowatch FL-03, and instruments were operated according to manufacturers' specifications.

3. RESULTS AND DISCUSSION

3.1 Water quality

Water quality parameters greatly influence the condition of coral reef and seagrass ecosystems and the abundance of associated biota in the waters. The results of measurements of physico-chemical parameters of intertidal waters at the research site are presented in Table 2.

The temperature range at both research sites is still in the normal range which value 27.5-29.3°C that supports the life of aquatic organisms, especially invertebrates. The normal temperature for benthic animal life is 25-33°C [13], so if the water temperature is exceeded 35°C, marine invertebrates are likely experience stress. Studies have shown that marine invertebrates are exposed to both acute and long-term thermal stress, especially in intertidal and shallow waters during various life stages [14]. However, low temperatures can also inhibit their acclimatization to hydrostatic pressure when they are outside their natural distribution [15].

The salinity range at both research site is considered optimum. Marine invertebrates, particularly benthic species, are especially susceptible to changes in environmental salinity due to their limited mobility and reduced tolerance to low-salinity conditions, this increased salinity levels are correlated with a decline in macroinvertebrate diversity and evenness, leading to a higher abundance of tolerant species [16, 17]. The salinity gradient plays a crucial role in species sorting of benthic invertebrates, where the niche factor of salinity, along with dispersal limitations, influences the community assembly of invertebrates in estuarine environments [18].

Table 2. Water quality parameters

Parameters	1	2	3	Optimum Value	Source
		Tabuhan Island			
Temperature (°C)	29.3	28.7	28.3	28-30	Government Regulation (PP) No.22/ 2021
Salinity (%)	33	34	34	33-34	
pH	8.3	8.2	7.9	7-8.5	
DO (mg/l)	6.2	6	5.5	> 5	
Current (m/s)	0.04	0.2	0.25	-	-
Depth (m)	2 – 3	2 – 3	2 – 3	-	-
Substrate	Coral, sand	Coral, seagrass	Seagrass, sand	-	-
		Bangsring Underwater			
Temperature (°C)	28	27.6	27.5	28-30	Government Regulation (PP) No.22/ 2021
Salinity (%)	34	34	33	33-34	
pH	8.1	8	8.3	7-8.5	
DO (mg/l)	6.9	7.4	8.2	> 5	
Current (m/s)	0.12	0.03	0.07	-	-
Depth (m)	2 – 5	2 – 5	2 – 5	-	-
Substrate	Coral	Sand, mud	Coral	-	-

The pH value at both observation locations has a range of values that are considered optimum. pH is a limiting factor for organisms that live in a body of water. Acidification causes low pH levels which can disrupt physiological cell processes, affecting metabolic, osmotic, and ionic pathways in marine animals [19]. Additionally, high pH values can result in increased algae production, subsequently reducing macroinvertebrate diversity [20]. Acidification also expected to negatively impact calcifying marine organisms by impairing their ability to build protective shells and exoskeletons, leading to dissolution and erosion [21], especially in gastropods.

DO (dissolved oxygen) conditions at both locations have a slightly different range of values and considered optimal. Location 1 (Tabuhan Island) showed DO values ranging from 5.5-6.2 mg/l while location 2 (Bangsring Underwater Beach) had a range of DO values of 6.9-8.2. Several studies have highlighted the significance of dissolved oxygen in shaping macroinvertebrate communities. Dissolved oxygen is a key environmental variable affecting benthic macroinvertebrate diversity and abundance [22, 23].

Current speed plays an important role in waters, for example, mixing of water masses, transport of nutrients, oxygen transportation. In both locations, the range of existing currents has a different magnitude. At the Tabuhan Island, the current speed that occurs is higher when compared to Bangsring Underwater. The waters of Tabuhan Island are located in the open sea, where the current flow from the Bali Strait has no barricade. In contrast to Tabuhan Island, the waters of Bangsring Underwater Beach are located on the eastern side of Java Island, where the current from the Bali Strait is obstructed by several land masses, and does not flow directly into the waters of Bangsring Underwater Beach. The alignment of benthic organisms with dominant currents indicates a significant impact of currents on the behavior and distribution of benthic biota [24]. Changes in bottom water ventilation and nutrient export driven by bottom currents are thought to influence variations in benthic faunal assemblages during climate events [25].

Apart from the water physical-chemical parameters, there are other abiotic factors such as substrate type that affect the distribution pattern of macroinvertebrates. Environmental conditions such as bottom substrate and depth can describe a very large variation in the presence of macroinvertebrates, so that differences in species are often found in different areas. Specifically, the presence of sandy substrates has been associated with higher macroinvertebrate diversity [1]. The type of substrate also affects the distribution of benthic macroinvertebrate feeding groups, underscoring the importance of substrate characteristics in determining community composition [26]. In the waters of Tabuhan Island, there are substrates in the form of sand, coral reefs, and seagrass beds. While in the waters of Bangsring Underwater Beach, the substrate is dominated by coral reefs. This can be one of the causes of higher indicator species diversity on Tabuhan Island compared to Bangsring Underwater Beach.

The geographical location is caused by the difference in parameters between the two locations. The most significant differences between the two locations are in temperature, DO (dissolved oxygen), and current speed. The strong currents of the Bali Strait directly expose Tabuhan Island to the open sea [27]. The lack of geographical barriers on Tabuhan Island allows for higher current speeds, as shown by the strong current velocity on Bangsring Underwater. Tabuhan's location in the open sea, more exposed to direct sunlight and ocean currents, may contribute to its higher temperatures, while Bangsring is more sheltered. Changes in water temperature will potentially reduce the solubility of oxygen in water, so it can be seen from the research results that the DO levels in Tabuhan are lower compared to Bangsring Underwater [28].

3.2 Relative abundance (Kr)

In this study, the biotic data collection method used was the Reef Check method. There are 9 indicator species in the Reef Check method, 6 of the 9 indicators were found on Tabuhan Island, and only 1 of the 9 indicators was found in the waters of Bangsring Underwater Beach. Indicator species found on Tabuhan Island include: long spined sea urchin (Diadema sp.), pencil urchin (H. Mammilatus), collector urchin (Tripneustes sp.), sea cucumber (Holothuridae), Triton (Charonia tritonis), and giant clam (Tridacna sp.). While in the waters of

Bangsring Underwater Beach only found Giant Clam (Tridacna sp.). The existence of macroinvertebrates that were successfully documented in the research area is presented in Figure 3.

The relative abundance in this study is presented in Table 3 and a graph that displays the percentage of relative abundance at each station is presented in Figure 4.

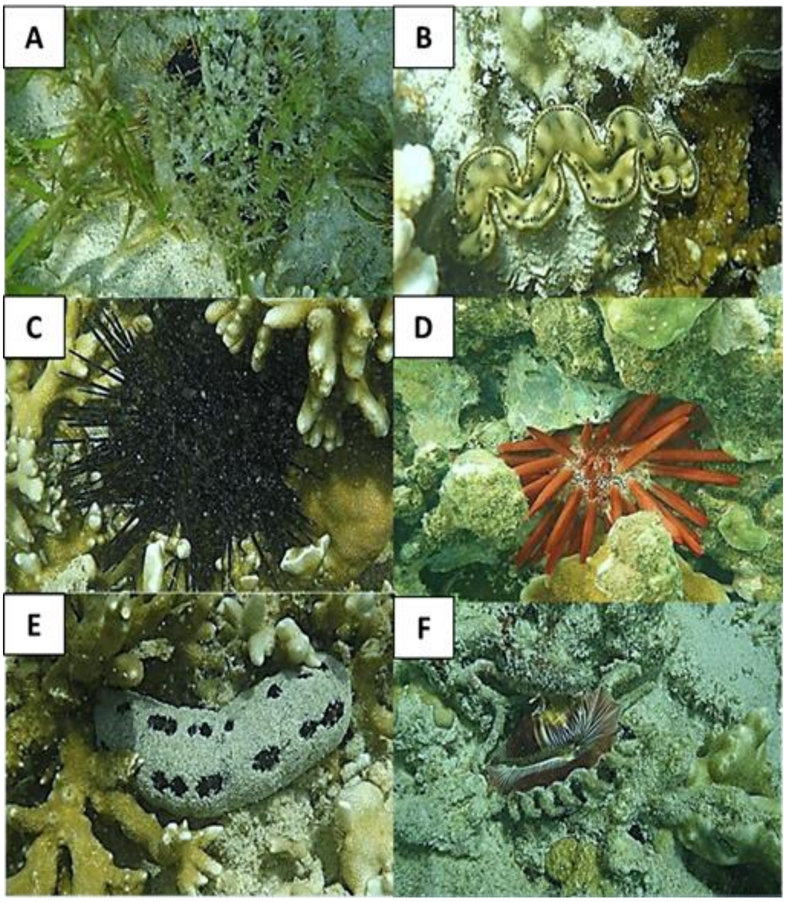
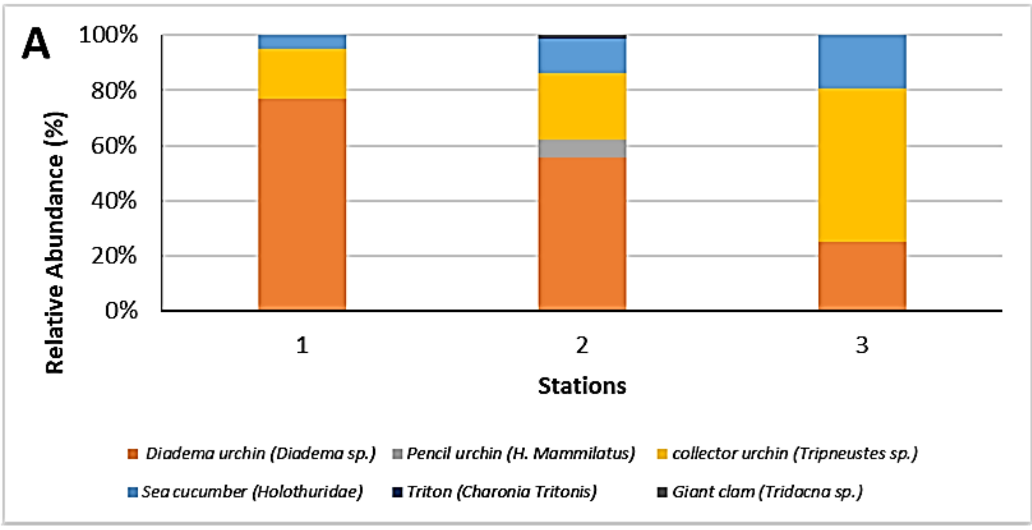


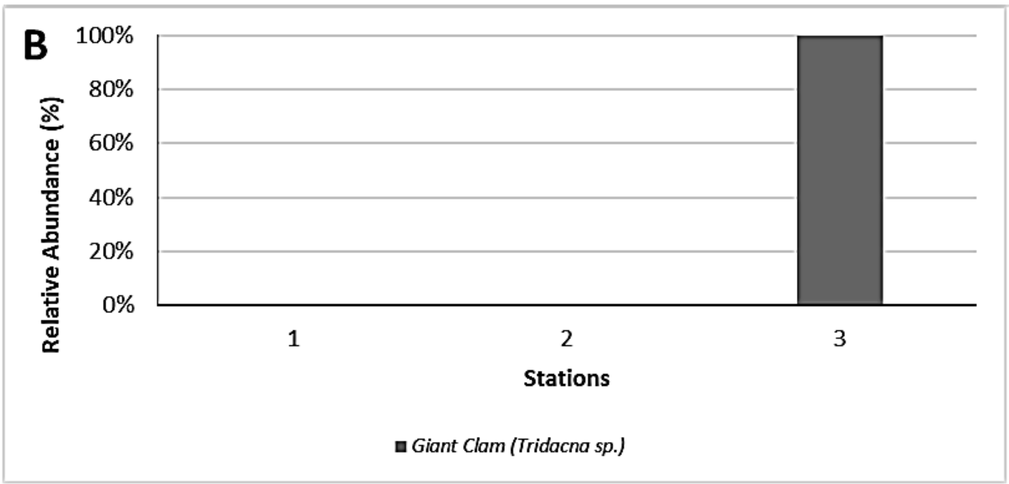
Figure 3. Documentation of macroinvertebrate found in research area: A. Collector Urchin (Tripneustes sp.), B. Giant Clam (Tridacna sp.), C. Long Spined Sea Urchin (Diadema sp.), D. Pencil Urchin (H. mammilatus), E. Sea Cucumber (Holothuridae), F. Triton (Charonia tritonis)

Table 3. Macroinvertebrate relative abundance

Species Name	Station			Number of Individuals	Relative Abundance
	I	II	III		
Tabuhan Island					
Banded coral shrimp	0	0	0	0	0.00%
Diadema urchin	104	72	31	207	53.49%
Pencil urchin	0	8	0	8	2.07%
Collector urchin	24	31	68	123	31.78%
Sea cucumber	7	16	24	47	12.14%
Crown of Thorns	0	0	0	0	0.00%
Triton	0	1	0	1	0.26%
Lobster	0	0	0	0	0.00%
Giant clam	0	1	0	1	0.26%
Number (N)	135	129	123	387	100.00%
Bangsring Underwater Beach					
Banded coral shrimp	0	0	0	0	0.00%
Diadema urchin	0	0	0	0	0.00%
Pencil urchin	0	0	0	0	0.00%
collector urchin	0	0	0	0	0.00%
Sea cucumber	0	0	0	0	0.00%
Crown of Thorns	0	0	0	0	0.00%
Triton	0	0	0	0	0.00%
Lobster	0	0	0	0	0.00%
Giant clam	0	0	1	1	100%
Number (N)	0	0	1	1	100.00%



(a) Location of Tabuhan Island



(b) Location of Bangsring Underwater Beach

Figure 4. Relative abundance graph (a). Location of Tabuhan Island, (b). Location of Bangsring Underwater Beach

In the waters of Tabuhan Island, the indicator species that has the highest percentage of relative abundance is Diadema urchin/long spined sea urchin (Diadema sp.), with a percentage of 53.49%. While triton (Charonia tritonis) and giant clam (Tridacna sp.) have the smallest percentage of relative abundance at 0.26%. The percentage of relative abundance of indicator species at each station is dominated by different species, especially at station 3 which is dominated by collector urchin (Tripneustes sp.) with a relative abundance of 55.28%.

The different types of substrates that exist in the three stations where at station 1 has a slightly sandy coral substrate type, station 2 has a combined substrate type between coral and sand inhabited by seagrasses, while at Station 3 has a substrate type dominated by seagrass beds. In the second location, Bangsring Underwater Beach, from the three stations only 1 indicator species was found, namely giant clam (Tridacna sp.) at station 3 with a total of 1 individual.

3.3 Diversity index (H')

The Diversity Index (H') is an index that explains how high the variety of species found in the area. In this study, the value of the diversity index at the research location is presented in Table 4.

In the research in the waters of Tabuhan Island, the results of the highest diversity index (H') were found at station 2 with moderate diversity criteria with a value of H' = 1.1370. While at stations 1 and 3 found a low diversity value, station 1 has a value of H' = 0.6614 and station 3 has a value of H' = 0.9938. Based on the results of this study, it shows that station 2 has the highest level of diversity and productivity of organisms compared to stations 1 and 3.

Table 4. Diversity index

Station	Index Value	Criteria
Tabuhan Island		
1	0.66	Low Diversity
2	1.14	Medium Diversity
3	0.99	Low Diversity
Bangsring Underwater Beach		
1	0	Low Diversity
2	0	Low Diversity
3	0	Low Diversity

The presence of macroinvertebrates in an area is influenced by both biotic and abiotic environmental factors. Intertidal zones, in particular, are subject to harsh conditions that can either increase or decrease species diversity depending on the circumstances [29]. The close connectivity between intertidal and subtidal habitats also affects species distribution and diversity [30]. Low diversity often occurs when the distribution of individual species is uneven, leading to dominance by certain species in specific areas. This imbalance is linked to each species' adaptation to factors such as substrate type, food availability, and environmental conditions.

Meanwhile a research by Isdianto et al. [5], with the same method and protocols showed the Jetty Station (JT) was dominated by Diadema sea urchins with the highest dominance index among all stations (> 0.80) and has the lowest diversity (H' between 0.08 to 0.26), indicating an unbalanced community. In addition, research by Mashar et al. [31] on Ponelo Island also stated the same results, that anthropogenic habitats with substrates that are more influenced by human activities, show lower diversity (H' = 1.3750). These studies showed intense human activities affected habitat quality and macroinvertebrate distribution, resulting in low species diversity.

3.4 Evenness index (E)

The evenness index explains the uniformity of species in a research location. The size of the evenness index value of a body of water shows how evenly the distribution of individuals or organisms in it as explained according to the statement of Jiang et al. [32] that the smaller the evenness index of a location, the distribution of the types of each individual is uneven, there is even a tendency for a body of water to be dominated by a particular species. The value of the evenness index (E) in this study is presented in Table 5.

Evenness (E) was highest at Tabuhan station 3 (E = 0.905) and moderate at stations 1 and 2 (E = 0.602 and 0.707, respectively), indicating a more balanced distribution of individuals among indicator taxa at Tabuhan. At Bangsring, E = 0 because only a single indicator individual (Tridacna sp.) was recorded site-wide, yielding complete dominance. These patterns emphasize a more equitable assemblage at Tabuhan relative to a simplified assemblage at Bangsring. Mechanistic interpretation (substrate configuration and human use) is summarized in 3.6.

Table 5. Evenness index

Station	Index Value	Criteria
Tabuhan Island		
1	0.60	Medium Uniformity
2	0.71	Medium Uniformity
3	0.90	High Uniformity
Bangsring Underwater Beach		
1	0	Low Uniformity
2	0	Low Uniformity
3	0	Low Uniformity

3.5 Dominance index (C)

The Dominance index (C) itself is an index explains the organisms that dominate a body of water. The high and low dominance of species in a water body is caused by several biotic and abiotic factors. The higher the dominance in a water body indicates the lower the uniformity value. The magnitude of the Dominance index value in this study is presented in Table 6.

Dominance (C) was highest at Tabuhan station 1 (C = 0.6277; moderate), indicating a concentration of individuals in a few indicator taxa. Stations 2 and 3 showed low dominance (C = 0.3885 and 0.4072), consistent with more even distributions. At Bangsring, station 3 exhibited complete dominance (C = 1.00) because only a single indicator individual (Tridacna sp.) was recorded. By definition, higher C denotes stronger dominance and lower community evenness [33]. The elevated C at Tabuhan station 1 reflects the large count of Diadema sp. (n = 104); mechanistic habitat drivers are addressed in 3.6.

Table 6. Dominance index

Station	Index Value	Criteria
Tabuhan Island		
1	0.63	Medium Dominance
2	0.39	Low Dominance
3	0.41	Low Dominance
Bangsring Underwater Beach		
1	0	Low Dominance
2	0	Low Dominance
3	1.00	High Dominance

3.6 Factors influencing macroinvertebrate community differences

We found a clear difference in macroinvertebrate community structure between Bangsring Underwater Beach and Tabuhan Island. Using the Reef Check approach (nine indicator species), six indicators were recorded at Tabuhan including Diadema sp., H. mammilatus, Tripneustes sp., Holothuridae, Charonia tritonis, and Tridacna sp.—whereas only one indicator (a single Tridacna sp.) was observed at Bangsring. Because indicator taxa do not capture the full macroinvertebrate assemblage, the results mainly reflect pressure-sensitive groups. The higher richness at Tabuhan is consistent with its seascape mosaic (coral reefs and seagrass meadows across all three stations), which offers shelter–foraging complements for urchins and holothurians (e.g., crevices in corals; refuge and feeding within seagrass) [34-37].

Regarding dominant taxa, the prevalence of Diadema at station 1 is consistent with access to protective coral structure, whereas Tripneustes typically occupies seagrass and sand–rubble habitats; these patterns align with shelter–foraging trade-offs in echinoids and the broad habitat tolerance of Tripneustes in seagrass systems [38-40].

Water quality (temperature, salinity, pH, DO) at both sites met PP No.22/2021 thresholds; only DO differed modestly and is unlikely to fully explain the stark community contrast. Instead, spatial habitat heterogeneity and anthropogenic disturbance are the most plausible drivers [41]. Tourism intensity (visitor numbers, snorkel/diver activity, boat traffic/anchoring) is substantially higher at Bangsring, visitor counts reportedly reached ~1,140,341 during 2015-2017 [42] and an official report of ~25,000 visitors during 24 Dec. 2017-1 Jan. 2018 [43]. Such activities are known to disturb corals and seagrass, resuspend sediments, and depress macroinvertebrate diversity [44-46]. Consequently, differences in abundance, diversity, evenness, and dominance are best interpreted as the combined effect of habitat structure and human pressure.

From a resilience perspective, the lower diversity and higher dominance at Bangsring suggest reduced capacity to recover from disturbance. Herbivorous macroinvertebrates (e.g., Diadema) help sustain coral health by suppressing algal overgrowth; their decline can impair nutrient cycling and other ecosystem functions, whereas more diverse assemblages (as at Tabuhan) support broader services and enhance reef resilience [47, 48].

3.7 Management recommendations and ecological implications

The management recommendations proposed here aim to restore and sustain local macroinvertebrate communities while advancing SDG 14 (Life Below Water) and SDG 12 (Responsible Consumption and Production) through ecosystem-based management and responsible tourism.

Comparative patterns between Tabuhan Island and Bangsring Underwater indicate that macroinvertebrate structure is governed chiefly by habitat complexity and human use, rather than water quality per se (temperature, salinity, pH, DO within standards at both sites). At Tabuhan, a coral–sand–seagrass mosaic supported six of nine Reef Check indicators and a more balanced assemblage; at Bangsring, only a single Tridacna individual was recorded, yielding E = 0 and C = 1.00. These contrasts are consistent with higher tourism intensity at Bangsring (≈1,140,341 visitors in 2015–2017) [42], which is known to increase contact, resuspension, and habitat abrasion, thereby suppressing macroinvertebrate diversity. Habitat mechanisms are detailed in 3.6.

To mitigate these impacts and preserve essential ecosystem services, several management interventions are recommended:

•Visitor and vessel regulation. Implement adaptive caps on daily visitors; designate boat lanes; prohibit anchoring over sensitive substrates; and install mooring buoys to minimize contact and resuspension [49].

•Spatial zoning. Ensuring that areas rich in complex substrates and seagrass beds are protected from intensive use and sedimentation [50]. Spatial zoning also allows sensitive habitats to recover and maintain ecosystem services.

•Community co-management and participatory monitoring. Engage local stakeholders to track indicator macroinvertebrates and compliance, increasing rule legitimacy and enabling rapid response to threshold breaches [51].

•Promote sustainable tourism practices through education and outreach to operators and visitors, focusing on minimizing contact with marine life, avoiding waste, and adhering to designated tourism zones [52].

•Habitat restoration and complexity enhancement. Where degradation has occurred, deploy seagrass transplantation and coral gardening; where appropriate, add artificial micro-substrates/reef units to facilitate settlement and recruitment [53, 54].

Diverse macroinvertebrate assemblages underpin algal control, nutrient cycling, and habitat engineering, thereby reinforcing coral-reef resilience [55, 56]. The framework is scalable and transferable to other Indonesian and Southeast Asian destinations, provided sites adopt explicit management triggers (e.g., visitor-day thresholds, turbidity caps, minimum urchin abundance) and track outcomes using a routine tourism-pressure index alongside macroinvertebrate indicators (see Methods). Taken together, these measures offer a practicable pathway to recover ecological function while maintaining economically viable marine tourism.

4. CONCLUSION

This study indicates that macroinvertebrate community structures in coral reef ecosystems are strongly influenced by a combination of environmental parameters and anthropogenic pressures. In Tabuhan Island, the presence of diverse substrates—including coral, sand, and seagrass beds—supported higher macroinvertebrate diversity (H' = 0.66–1.14), evenness (E up to 0.90), and relatively low to moderate dominance (C = 0.39–0.63). In contrast, Bangsring Underwater Beach exhibited a severe collapse in diversity and evenness indices (H' and E = 0) and complete dominance by a single species (C = 1.00), despite both sites meeting optimum water quality standards for temperature, salinity, pH, and dissolved oxygen. These findings confirm that habitat complexity is essential for supporting resilient macroinvertebrate communities, while intensive tourism activities—such as high visitor numbers and boat traffic—are the primary drivers of biodiversity loss and reduced ecosystem resilience at Bangsring.

Management should therefore prioritize an integrated package: visitor/vessel controls (including no-anchoring and mooring buoys), spatial zoning that steers high-use activities away from sensitive substrates, targeted habitat restoration (e.g., seagrass and coral out-planting), and community-based monitoring of indicators. Implemented together, these measures support SDG 14 (Life Below Water) and SDG 12 (Responsible Consumption and Production) by aligning biodiversity conservation with responsible coastal tourism.

A key limitation of this study is its cross-sectional design and focus on indicator species; longer-term ecological monitoring, the inclusion of additional biotic and abiotic variables, quantitative tourism metrics (e.g., boat trips, diver-hours, anchoring events), and the use of advanced analytical approaches could provide deeper insights into resilience mechanisms and recovery trajectories. Future work should incorporate co-temporal pressure logging and expanded, habitat-stratified sampling, ideally with before–after or control–impact designs and multivariate models, to test mechanistic links and recovery trajectories more explicitly. Despite these constraints, the proposed integrated framework is scalable and offers a practical basis for balancing tourism and conservation across high-pressure coral-reef destinations in Indonesia and the wider Southeast Asian region.

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