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Porifera community structure as a bioindicator of tourism impacts at Iboih Beach, Sabang

Muhammad Ridhwan [a, 1, *], Nurlena Andalia [b, 2], Husna [c, 3]

[a] Department of Biology Education, Universitas Serambi Mekkah, Banda Aceh, Indonesia
[b] Master of Biology Education, Universitas Serambi Mekkah, Banda Aceh, Indonesia
[c] Department of Public Health, Universitas Serambi Mekkah, Banda Aceh, Indonesia
[1] muhammad.ridhwan@serambimekkah.ac.id; [2] nurlena.andaliaz@serambimekkah.ac.id;
[3] husna@serambimekkah.ac.id
* Corresponding author

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ABSTRACT

This study aims to identify the composition, distribution, and diversity of Porifera species in the coral reef ecosystem of Iboih Beach, Sabang, as a scientific basis for marine biodiversity conservation and the development of invertebrate zoology learning materials in higher education. The research was conducted from June to July 2025 using line transect and 1 m² quadrat sampling methods across three shallow reef zones. A total of 21 Porifera species were identified, predominantly from the class Demospongiae, with Spongia, Haliclona, and Petrosia as dominant genera. Species identification was performed through both macroscopic morphological observations and microscopic analysis of spicule structures. The Shannon-Wiener diversity index (H′) ranged from 1.95 to 2.67, indicating a moderate level of diversity. Species distribution was strongly influenced by substrate type, with the highest abundance recorded on hard coral substrates, while sandy areas showed lower diversity. Approximately 20% of sponge colonies were partially covered by fine sediment and macroalgae, especially near snorkeling zones, suggesting ecological pressure from tourism. These findings provide essential baseline data for long-term biodiversity monitoring, promote sustainable marine tourism, and support the contextualization of zoological education through local marine resources.

Conflict of interest: The authors declare that they have no conflicts of interest.

Introduction

Coral reef ecosystems around the world harbor an extraordinary diversity of marine organisms, many of which play crucial ecological and biochemical roles. Among these, sponges (phylum *Porifera*) are recognized for their contribution to habitat complexity,

nutrient cycling, and as indicators of environmental health[1,2]. Their capacity to produce diverse bioactive compounds has also attracted increasing interest in marine pharmacology[3]. In tropical regions such as Indonesia, which possesses some of the richest marine biodiversity on Earth, sponges are abundant and play a particularly vital role in coral reef systems. The presence of sponges significantly enhances the productivity and resilience of reef ecosystems[4].

Recent studies estimate that over 8,500 sponge species (*Porifera*) have been identified globally, with a large proportion inhabiting tropical marine ecosystems, including those in Indonesian waters[5]. Despite this richness, comprehensive documentation and species inventories in many coastal regions of Indonesia remain limited. This lack of baseline data poses a serious challenge for effective biodiversity monitoring and conservation planning. At the same time, Indonesian coral reefs are increasingly threatened by anthropogenic pressures such as coastal development, pollution, and climate change factors, known to contribute to the degradation and population decline of sponge communities[6,7]. These knowledge gaps, coupled with mounting ecological stress, underscore the urgent need for localized studies on sponge diversity and distribution.

As the most ancient multicellular animals, sponges (*Porifera*) play a pivotal role in understanding the early evolution of Metazoa[8]. Their simple yet functional anatomy provides valuable insights into marine taxonomy, phylogeny, and ecology[1,9]. Documenting sponge species in specific habitats not only advances biodiversity conservation but also enhances opportunities for bioprospecting natural bioactive compounds[3].

The coastal region of Sabang, particularly Iboih Beach, hosts one of Indonesia's most biodiverse coral reef ecosystems and has been designated as a marine conservation area[10]. Despite its ecological importance, studies specifically documenting sponge (*Porifera*) diversity in this area remain limited. This gap is concerning, as Iboih Beach is also a major hub for diving and snorkeling tourism, which brings increasing human interaction with benthic habitats[11]. Unregulated tourism, such as anchoring, trampling by snorkelers, and increased boat traffic, can cause direct physical damage to sponge colonies, alter substrate stability, and degrade water quality, ultimately threatening the persistence of these ecologically valuable species[12]. Understanding local sponge diversity is therefore crucial not only for conservation efforts but also for informing sustainable tourism practices that balance ecological integrity with economic interests.

Conducting a Porifera inventory at Iboih Beach is ecologically and educationally significant, as it establishes a vital baseline database for monitoring reef health, detecting changes in community composition, and guiding evidence-based conservation strategies—aligned with Sustainable Development Goal (SDG) Life Below Water—while also contributing valuable scientific knowledge for local stakeholders, enhancing public awareness of marine biodiversity, and providing authentic, context-specific learning material for invertebrate zoology education at the university level.

Marine sponges (Porifera) are widely recognized for their potential as sources of bioactive compounds, with numerous studies highlighting their pharmacological properties. Notably, *Theonella swinhoei* has been shown to produce metabolites with anti-inflammatory and anticancer activities[13-15], underscoring the value of sponge-derived compounds in biomedical research. This reinforces the critical importance of documenting and inventorying sponge species, especially in biodiverse and ecologically complex regions such as Indonesia, where unique environmental conditions can give rise to distinct chemical profiles[16]. Each marine habitat may harbor sponge species with novel bioactive compounds, making localized exploration essential not only for bioprospecting but also for informing conservation strategies. Moreover, systematic species documentation provides essential baseline data for monitoring ecosystem health, detecting biodiversity changes, and supporting the designation of marine protected areas. Despite their promise, many Indonesian coastal ecosystems remain

poorly explored, leaving gaps in our understanding of both sponge biodiversity and its chemical potential. In this context, the present study focuses on identifying and characterizing *Porifera* species in the coral reef ecosystem of Iboih Beach, Sabang, thereby contributing to the national biodiversity inventory, enriching invertebrate zoology education with locally grounded content, and laying a scientific foundation for future pharmaceutical research targeting marine-derived bioactive compounds.

Based on this background, this study aims to identify and document the species composition of *Porifera* in the coral reef ecosystem of Iboih Beach, Sabang. The findings are expected to contribute significantly to the scientific inventory of Indonesia's marine biodiversity, provide baseline data to support conservation strategies in line with Sustainable Life Below Water, and enrich invertebrate zoology education through the integration of locally sourced biological data. Additionally, this research lays the groundwork for future bioprospecting efforts, particularly in the exploration of marine-derived bioactive compounds with potential pharmaceutical applications.

Method

Research Location and Time

This study was conducted in the coastal waters of Iboih Beach, Teupin Layeu Village, Suka Karya District, Sabang City, Aceh Province (Fig. 1). The site was selected due to its status as a marine tourism zone characterized by well-preserved coral reefs and relatively high biodiversity. Field data were collected from June to June 2024, with scheduling adapted to tidal patterns and prevailing weather conditions.

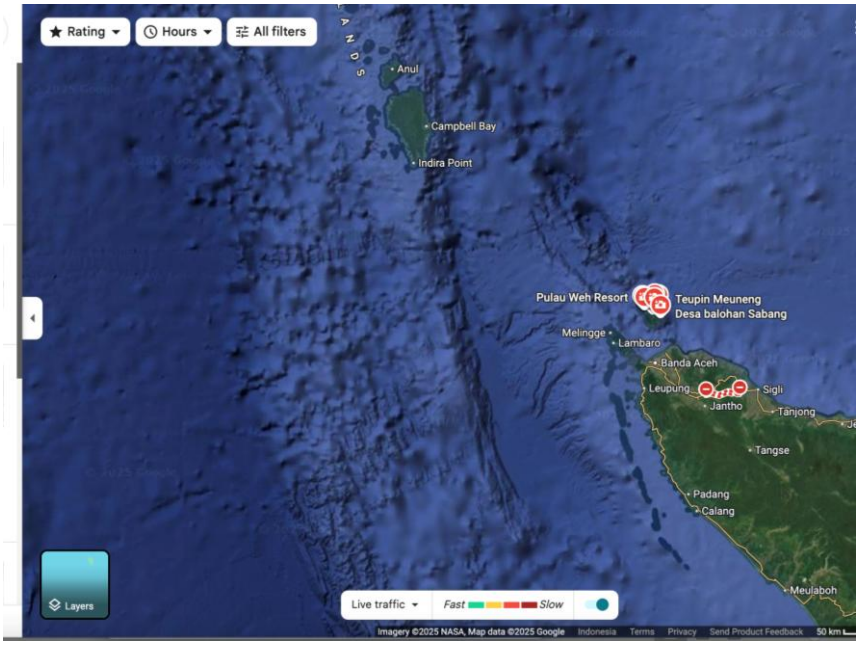

Fig. 1 | Coastal map of Iboih Beach, Teupin Layeu Village, Suka Karya District, Sabang City, Aceh Province

Research Design

This study employed a field-based survey design aimed at describing and characterizing the morphological traits, spatial distribution, and species diversity of Porifera in the study area. Primary data were collected through direct observation, specimen sampling, and underwater visual documentation. This approach was selected to generate baseline ecological data on local sponge communities, in line with the study's objectives of supporting biodiversity assessment and conservation planning[10,11].

Tools and Materials

The equipment used in this study was grouped into three main categories. Sampling tools included a 1 m² quadrat frame for defining observation plots and a roll meter for line transect measurement. Documentation tools comprised a digital underwater camera for recording morphological characteristics, a handheld GPS for logging coordinates, and field worksheets for data recording. Preservation materials consisted of ziplock plastic bags, sample labels, and 70% ethanol for temporary specimen fixation. Basic snorkeling and diving gear (masks, snorkels, fins) supported underwater observations and sample collection. A Porifera identification guidebook[1] was used for species classification in the field and laboratory.

Sampling Techniques

Data collection was conducted using line transect–quadrat sampling methods[17]. Three transects, each 50 meters in length, were laid perpendicular to the shoreline to capture habitat gradients from the coast to the reef edge within the shallow coral zone. Five 1 m² plots were established along each transect at 10-meter intervals, providing adequate spatial representation for assessing benthic community composition. All visible Porifera individuals within the plots were recorded, and representative specimens, particularly those with uncertain field identification or overlapping morphological traits, were collected for further taxonomic analysis in the laboratory[9].

Specimen Identification

Species identification was initially conducted through macroscopic morphological observations in the field. To confirm species-level classification, microscopic examination of spicules was performed in the laboratory. Spicule slide preparations followed standard protocols outlined by Rützler[18]. Taxonomic determination was based on the most recent identification keys from the World Porifera Database[5] and supported by other relevant taxonomic references[1,8].

Data Analysis

Data on species type, individual counts, and spatial distribution were analyzed descriptively and presented in the form of tables, graphs, and distribution maps. The species diversity in each transect was quantified using the Shannon-Wiener diversity index (H′)[19], which accounts for both species richness and evenness. The resulting H′ values were interpreted based on established ecological benchmarks, where values between 1.5 and 3.5 indicate moderate diversity. To assess ecosystem health, the diversity index and distribution patterns were compared with findings from similar reef ecosystems in other coastal regions[6].

Results and Discussion

This study documented a total of 21 Porifera species in the coastal waters of Iboih Beach, Sabang, based on observations from three line transects comprising 15 plots. The identified species belonged to two taxonomic classes: *Demospongiae*, which dominated the assemblage, and *Calcarea*, represented by a single species. Notably, no representatives of the class *Hexactinellida* were recorded, which may reflect the shallow and high-energy conditions of the study area, as this group typically inhabits deeper, colder waters. These findings highlight the predominance of shallow-water sponge taxa and provide valuable insights into the benthic community structure of coral reef habitats in the region.

Composition of Porifera types

The majority of species identified in this study belong to the class *Demospongiae*, with dominant representation from the genera *Spongia*, *Haliclona*, and *Petrosia*. Only a single species from the class *Calcarea*, *Clathrina blanca*, was recorded, primarily inhabiting shallow coral microhabitats. This limited representation is consistent with the ecological niche of *Calcarea*, which tends to favor specific limestone or dead coral habitats and has a lower

tolerance to sedimentation and physical disturbance[20]. As shown in Table 1, species such as *Haliclona fascigera*, *Theonella swinhoei*, and *Petrosia nigricans* were among the most frequently encountered, suggesting their strong adaptability to the environmental conditions of Iboih's reef zone. This dominance aligns with global patterns, where over 85% of described sponge species are classified within *Demospongiae* due to their morphological adaptability and resilience in various reef environments[5,21]. In contrast, no species from the class *Hexactinellida* were found, likely due to their preference for deeper, colder, and more stable substrates. This taxonomic distribution reflects the dominance of sponges adapted to high-light, dynamic shallow-water environments, indicating a healthy and structurally complex coral reef system in Iboih Beach. These results emphasize the importance of substrate diversity in supporting sponge richness and composition. The presence of diverse Porifera groups in relatively shallow, tourist-exposed zones also highlights the ecological sensitivity of these areas. Therefore, conserving these habitats directly contributes to Sustainable Development Goal (Life Below Water), particularly in maintaining marine biodiversity and promoting sustainable use of reef ecosystems.

Table 1 | Composition of Porifera types in Iboih Beach, Sabang

No	Class	Genus	Spesies	Number of Individuals
1	Calcarea	Clathrina	Clathrina blanca	7
2	Demospongiae	Spongia	Spongia obscura shaggy	5
3	Demospongiae	Spongia	Spongia virgultosa	6
4	Demospongiae	Spongia	Spongia obscura smooth	6
5	Demospongiae	Haliclona	Haliclona fascigera	7
6	Demospongiae	Liosina	Liosina paradoxa	6
7	Demospongiae	Coelocarteria	Coelocarteria agglomerans	7
8	Demospongiae	Haliclona	Haliclona sp.	8
9	Demospongiae	Theonella	Theonella swinhoei	7
10	Demospongiae	Clathria	Clathria basilana	5
11	Demospongiae	Acanthella	Acanthella cavernosa	6
12	Demospongiae	Petrosia	Petrosia nigricans	7
13	Demospongiae	Niphates	Niphates olemda	7
14	Demospongiae	Ircinia	Ircinia ramose	5
15	Demospongiae	Callyspongia	Callyspongia joubini	3
16	Demospongiae	Paratetilla	Paratetilla bacca	4
17	Demospongiae	Dysidea	Dysidea cinerea	3
18	Demospongiae	Gelliodes	Gelliodes petrosioides	3
19	Demospongiae	Tethya	Tethya robusta	7
20	Demospongiae	Biema	Biema fortis	6
21	Demospongiae	Epipolasis	Epipolasis suluensis	4

The dominance of *Demospongiae* in this tropical reef system is ecologically consistent with their morphological and physiological adaptations to shallow, dynamic marine environments. Many genera observed, such as *Spongia*, *Haliclona*, and *Petrosia* exhibit complex aquiferous systems and flexible body forms, which enhance their capacity to withstand moderate to strong currents and fluctuating nutrient levels[22,23]. These features allow them to maintain efficient filtration and nutrient acquisition under varying physical conditions.

Additionally, these genera are often associated with dense communities of microbial symbionts that contribute to nutrient cycling, including the transformation of dissolved organic matter into usable particulate forms, an essential process for sustaining reef

productivity[24]. The presence of such sponge-microbe systems highlights the integral role of Porifera in ecosystem functioning beyond their structural contributions to benthic habitats.

Clathrina blanca, the only species from the class *Calcarea*, was found in shallow zones with calcareous substrates, likely dead coral or limestone outcrops. This distribution is consistent with the known habitat preferences of *Calcarea*, which generally inhabit nutrient-poor, stable microhabitats with limited water movement[20]. Their localized presence reinforces the substrate specificity of certain Porifera taxa.

Comparative studies from the Indo-Pacific, including regions such as the Great Barrier Reef, the Philippines, and Papua New Guinea, have similarly reported *Demospongiae* as the dominant class, with a few *Calcarea* species occurring in specific niches[25,26]. The frequent occurrence of *Haliclona fascigera*, *Spongia obscura*, and *Petrosia nigricans* at Iboih Beach further corroborates findings from other reef systems where these taxa are typically associated with healthy coral environments[23].

Environmental conditions at Iboih, such as relatively clear water, moderate current regimes, and an abundance of hard coral substrate, provide a suitable habitat for diverse sponge communities[9]. However, localized sedimentation, likely originating from tourism-related disturbances, may limit the distribution of sponges with asconoid or siconoid canal systems that are more sensitive to pore blockage by fine particles[27].

The moderate Shannon-Wiener diversity index values ($H' = 1.95–2.67$) observed across transects suggest that the reef remains moderately biodiverse, supporting a range of functional groups while also showing signs of disturbance[11]. This underscores the need for targeted protection measures in snorkeling areas and controlled boat pathways to reduce physical and sedimentation stress on sponge habitats[23].

Importantly, the detection of genera such as *Theonella* and *Petrosia* adds applied value to the ecological findings. These genera are known producers of secondary metabolites with pharmaceutical potential, including anticancer and anti-inflammatory compounds[3,28]. Their presence reinforces the importance of preserving sponge diversity not only for ecosystem stability but also for future bioprospecting opportunities.

In summary, the Porifera community at Iboih Beach reflects the typical taxonomic and ecological structure of tropical coral reef systems, with *Demospongiae* dominance, niche-specific *Calcarea*, and functionally important microbial associations. These findings contribute to the growing body of knowledge on Indo-Pacific sponge diversity and highlight the urgent need for sustainable management of reef ecosystems under increasing tourism pressure.

Species Distribution in Transects

The distribution patterns of Porifera in Iboih Beach varied across different substrate types. The highest species richness was recorded in transects with corrugated hard coral substrates, followed by mixed sand-coral areas, while pure sand zones supported the fewest species. This trend reflects the ecological preference of most sponges for stable, hard surfaces that facilitate attachment and colony growth. Species such as *Spongia obscura* and *Haliclona fascigera* were predominantly found in areas with dense coral cover and high water clarity, suggesting their reliance on well-structured reef habitats.

Sponge distribution at Iboih Beach was strongly influenced by substrate type, with the highest species richness and abundance recorded in transects dominated by hard coral substrates. These stable and complex surfaces, comprising live corals, dead coral heads, and coral rubble, provide essential attachment points for sessile organisms like Porifera, enabling larval settlement and colony development[9,26]. Genera such as *Spongia*, *Haliclona*, and *Petrosia* were most commonly found in these areas, consistent with their known preference for structurally complex and well-illuminated reef habitats[21,25].

A notable pattern observed was the *patchy distribution* of sponge colonies, particularly in Transects A and B, where certain plots had high individual counts while adjacent plots

recorded few or none. This spatial heterogeneity likely results from microhabitat variability, competition with macroalgae, and localized sedimentation. In contrast, transects located in sandy or sand-coral mixed zones showed reduced species diversity and lower individual abundance. This is attributed to the inherent instability of sandy substrates, which are prone to shifting and lack the firmness required for sponge larval attachment[21]. While some sponges are capable of partial burial or attachment to mobile debris, such adaptations were not commonly observed in this study, further supporting the substrate-dependence of most species encountered.

Microhabitat variables, including current velocity, water clarity, and sedimentation, also played key roles in shaping sponge distribution. Moderate to strong water currents, characteristic of the hard substrate zones, enhance the delivery of suspended food particles and promote efficient filter feeding[7,9]. Conversely, areas with high levels of fine sediment, especially near transects adjacent to snorkeling activity zones, showed visible smothering of sponge surfaces by silt and macroalgae. These conditions are particularly detrimental to species with simple aquiferous systems (asconoid and siconoid), which are more vulnerable to pore blockage[27].

These findings are ecologically significant, as they suggest that sponge distribution is closely tied not only to substrate availability but also to fine-scale environmental gradients. Moreover, the observed dominance of filter-feeding sponges in structured reef zones underscores their role in the *sponge loop,* a nutrient cycling process where sponges convert dissolved organic matter (DOM) into particulate matter, thereby sustaining coral reef productivity. This function will be further discussed in the following section.

A clear example of spatial heterogeneity, or "patchy distribution," was observed in Transects A and B. In these transects, certain plots supported dense sponge assemblages, while adjacent plots had very few or no individuals. This distribution pattern, also reported in other Indo-Pacific and Caribbean reef systems, results from interactions among substrate variation, spatial competition with macroalgae, and localized bioerosion[23,26]. Such patchiness reflects the high sensitivity of sponges to micro-scale habitat conditions and competition dynamics.

The ecological role of sponges in these reef systems extends beyond benthic coverage. Their capacity to process large volumes of water up to ten times their body volume per minute facilitates the uptake and conversion of dissolved organic matter (DOM) into particulate organic matter via the *sponge loop*[7,23]. This function not only sustains sponge biomass but also supports microbial and detritivore food webs, reinforcing the trophic stability of coral reef ecosystems.

Given the spatial patterns and sensitivity of sponge distribution observed, the results provide important baseline data for long-term reef monitoring. Distributional information can be used as an ecological indicator of substrate health and as a scientific basis for designing tourism zoning plans. Specifically, protecting high-density sponge zones from direct tourist access, establishing regulated snorkeling routes, and limiting anchoring activity near sponge-rich substrates could help minimize damage and maintain benthic biodiversity[11]. These measures are essential for integrating sponge conservation into broader coastal ecosystem management in Sabang.

Diversity Index

The Shannon-Wiener diversity index (H′) calculated for each transect ranged from 1.95 to 2.67, with a mean value of 2.31. This range indicates moderate species diversity, which is typically associated with ecosystems experiencing balanced environmental conditions and moderate levels of disturbance[19]. This characteristic is also found in tropical coral reef systems, which have relatively stable ecological conditions[9,26]. The absence of overwhelming dominance by a single species suggests that the sponge community structure remains balanced and functionally intact. At Iboih Beach, this moderate diversity likely reflects a reef

environment that, while still structurally complex and biologically productive, is beginning to show localized stress such as sedimentation and macroalgal overgrowth in some plots.

Moderate diversity levels are ecologically significant because they reflect a resilient community in which multiple species contribute to essential ecosystem functions. High species evenness implies that functional roles such as nutrient cycling, space competition, and filter feeding are shared across different taxa, reducing the ecosystem's vulnerability to disturbances[23,29].

The absence of highly dominant species and the relatively even distribution of species suggest that the sponge community retains functional resilience. However, the variability in H′ values across transects highlights the influence of substrate heterogeneity and human activity gradients within the reef zone. From a conservation perspective, this moderate diversity level signals the need for targeted management to prevent further degradation.

Given the dynamic nature of coastal ecosystems and increasing tourism pressure, periodic monitoring of benthic diversity using H′ and complementary indicators will be essential for detecting ecological shifts early, guiding adaptive conservation strategies, and maintaining the ecosystem services provided by sponge communities.

This study's findings are consistent with the sponge loop model proposed by de Goeij et al.[7], wherein sponges contribute to the transformation of dissolved organic matter (DOM) into particulate organic matter that becomes available to other reef organisms. A moderate but stable H′ value indicates the sustained operation of this nutrient-recycling mechanism, which enhances energy transfer and supports reef productivity[27].

When compared with other Indo-Pacific reef ecosystems, the diversity values observed at Iboih Beach fall within a similar range. H′ values between 2.0 and 2.8 on Australian reefs, depending on site-specific variables such as substrate complexity, hydrodynamics, and anthropogenic influence[25]. The comparable values at Iboih suggest that, despite increasing tourism pressure, the reef structure, particularly in hard-substrate zones, still supports healthy sponge assemblages.

Nevertheless, localized signs of ecological stress were evident. Some transect plots, especially those adjacent to high-use snorkeling zones, exhibited sediment accumulation and macroalgal overgrowth. These conditions are known to hinder sponge feeding efficiency and reduce species diversity, particularly among species with less efficient aquiferous systems[30]. Without mitigation, continued sedimentation may progressively reduce sponge richness in vulnerable zones.

Importantly, sponge diversity can also serve as a biological indicator of water quality. Sponges are highly sensitive to changes in nutrient concentrations, turbidity, and temperature fluctuations, making them valuable proxies for assessing reef health[20,29]. The moderately stable H′ values found in this study suggest that environmental conditions remain generally favorable, although these results should be corroborated with direct physicochemical water quality measurements.

Given these findings, integrating H′-based diversity monitoring into long-term reef management strategies is both feasible and beneficial. Regular assessments of benthic diversity, particularly of key indicator taxa like Porifera, can provide early warnings of ecological degradation and help inform zoning decisions for tourism and conservation[11].

In conclusion, the Porifera diversity index at Iboih Beach reflects a moderately healthy reef environment with resilient community dynamics. However, proactive measures are necessary to control sedimentation and physical disturbances, ensuring that sponge diversity and associated ecosystem services are preserved in the face of growing tourism activity[23,31].

Additional Findings

Field observations at Iboih Beach revealed significant ecological stress on Porifera communities, particularly in areas with high tourist activity like Transect B. Sponges in these zones were often partially covered by fine sediment and competing macroalgae.

Sedimentation, likely resulting from foot traffic, motorboat propellers, and anchor drag, threatens to clog sponge filtration systems, impair choanocyte function, and suppress biomass growth[32]. Similarly, macroalgal overgrowth obstructs sponge ostia, limiting filtration and potentially triggering reef-wide phase shifts from coral to algae-dominated systems[33,34].

In addition to sedimentation and algal competition, direct physical damage to sponges, such as torn tissues and broken branches, was documented in plots closest to high-traffic entry points. These injuries are consistent with impacts from fins, diving equipment, and anchors, as reported in previous studies on marine tourism[35]. However, despite these pressures, the sponge community demonstrated a degree of ecological resilience. Signs of natural regeneration, including budding and new colony formation, were observed in several species, particularly *Haliclona* and *Spongia*, suggesting an active, though stressed, recovery process[36].

The study also identified sponge species with significant biotechnological value. The presence of *Theonella swinhoei* and *Petrosia nigricans* confirms that the site hosts important sponge-microbe holobionts known to produce compounds with antimicrobial, anticancer, and anti-inflammatory properties[16,28]. The health of these complex systems serves as a valuable bioindicator, offering an early warning for ecosystem shifts caused by anthropogenic stressors.

Collectively, these findings highlight an urgent need for integrated reef management at Iboih Beach. To mitigate ongoing damage, strategies such as establishing delineated snorkeling trails, creating anchor-free zones, implementing sediment control measures, and providing educational outreach for tourists are strongly recommended. Incorporating long-term monitoring of Porifera communities into conservation programs is critical, acknowledging their vital ecological roles and their sensitivity as indicators of overall ecosystem health[11].

Conclusion

This study recorded a total of 21 Porifera species in the coral reef ecosystem of Iboih Beach, Sabang, with a clear dominance of the class *Demospongiae*, while *Calcarea* was represented by a single species inhabiting calcareous microhabitats. Species richness and composition were strongly influenced by substrate type, with hard coral areas supporting higher abundance and diversity, particularly of *Spongia obscura*, *Haliclona fascigera*, and *Petrosia nigricans*. The calculated Shannon-Wiener diversity index (H′) ranged from 1.95 to 2.67, indicating a moderate level of diversity consistent with moderately disturbed but functionally resilient reef environments. This diversity supports key ecological processes such as nutrient recycling through the sponge loop. Observed ecological pressures, including sediment deposition, macroalgal overgrowth, and physical damage in transects near snorkeling zones, highlight the vulnerability of sponge communities to unregulated tourism. Nevertheless, evidence of natural regeneration and the presence of species with known bioactive potential underline the ecological and biotechnological importance of these habitats. These findings underscore the need for continued biodiversity monitoring and the implementation of sustainable marine tourism practices. The data also provide a valuable foundation for conservation planning and for integrating locally relevant content into marine biology education.

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Author contributions

All authors contributed to the conception and design of the study. Material preparation, data collection, and analysis were performed by **[Muhammad Ridhwan]**, **[Nurlena Andalia]**, and **[Husna]**. The first draft of the manuscript was written by **[Muhammad Ridhwan]**, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.