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Substrate Composition and Ecological Dynamics in Marine Environments Along the Northern Coast of Langkawi

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Abstract

A marine habitat mapping study using an Acoustic Ground Discrimination System (AGDS) was conducted at nine different locations in Northern Langkawi: Teluk Tanjung Tembun, Teluk Datai, Teluk Sungai Langgara, Pulau Jemuruk, Teluk Yu, Pulau Dangli, Pulau Gasing, Pulau Pasir, and Teluk Pasir Panjang. Depth profiles revealed distinct characteristics at each site. Greater depths (exceeding 15 m) were recorded at Pulau Dangli, Pulau Gasing, and Pulau Pasir, while shallower conditions (1.1 to 4.4 m) were observed at locations such as Teluk Yu. The distribution of hard substrates and algae-covered dead corals indicated dynamic ecological changes. Pulau Jemuruk exhibited the highest percentage (15.16%), whereas Teluk Datai recorded a lower distribution (3.08%). Rocky substrate distribution showed spatial heterogeneity across Pulau Jemuruk, Pulau Dangli, Pulau Gasing, and Pulau Pasir. Overall, Teluk Datai demonstrated extensive coral cover (38,896 m^2), while Teluk Tanjung Tembun displayed moderate coverage (10,821 m^2). Furthermore, Teluk Datai recorded the largest extent of sandy substrate distribution (1,125,503 m^2), whereas Pulau Gasing showed the smallest coverage (86,959 m^2). Finally, Teluk Pasir Panjang exhibited a significant distribution of sandy silt and clay (138,645 m^2). This holistic analysis provides a framework for effective conservation efforts and enables the development of strategic management plans. The findings underscore the importance of sustainable, site-specific conservation strategies tailored to the unique challenges of each location, ultimately contributing to the preservation of coral diversity and overall marine ecosystem health.

Keywords: Acoustic Ground Discrimination System (AGDS); Marine Habitat Mapping; Substrate Distribution; Coral Reef; Northern Langkawi

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Introduction

In general, water clarity is a key factor in determining an ecosystem's health status and the effectiveness of environmental management. However, recent evidence shows that ecosystems with turbid water conditions can also support healthy coral reef environments [1]. In Malaysian waters, the northern region of the Langkawi archipelago represents an excellent case study, where many coral colonies thrive in naturally turbid conditions [2]. Despite reduced water clarity, several coral species are able to survive and persist in these environments.

Because data for mapping these unique marine habitats are limited, current knowledge of coral reef resilience in turbid waters remains insufficient. Previously unexplored mechanisms may exist that, if investigated, could reveal novel and valuable insights. This study aims to contribute data supporting the sustainable management of this region.

A commonly cited limitation in marine habitat mapping is the constraint of satellite imaging in conditions of low water clarity or when information is required from deeper marine environments. According to Foster *et al.,* [3], the accuracy of data obtained from aerial and satellite imagery is largely restricted to moderately shallow waters and coastal zones, while mapping deeper marine areas remains challenging. For instance, in the United States, water depth and clarity limitations prevented mapping more than 55% of the Florida Keys National Marine Sanctuary (approximately 1,540 square nautical miles) [4]. Therefore, this study seeks to investigate benthic characteristic patterns in turbid waters using a more practical approach: hydroacoustic signal analysis.

Marine habitat maps provide valuable information on the spatial distribution and diversity of substrate types and marine habitats. Such data can be utilised for biodiversity conservation purposes

and to assist in identifying potential areas for designation as Marine Protected Areas (MPAs), as well as enhancing fisheries management and coastal development planning [5, 6].

The objectives of this study were to obtain depth profiles to determine the ecological dynamics of the northern region of Langkawi. The study also aimed to identify and characterise the composition of substrate types in the region. Additionally, it seeks to provide preliminary information on the spatial extent of coral cover in the study area to support the future planning, design, protection, and management of this region.

Methodology

Study area

The study area is located in the northern region of the Langkawi Archipelago (Figure 1), where most coral colonies exist in turbid water conditions. It comprises nine sites: (i) Teluk Tanjung Tembun, (ii) Teluk Datai, (iii) Teluk Sungai Langgara, (iv) Pulau Jemuruk, (v) Teluk Yu, (vi) Pulau Dangli, (vii) Pulau Gasing, (viii) Pulau Pasir, and (ix) Teluk Pasir Panjang. This area lies approximately 30 km west of the northern tip of Peninsular Malaysia, near the maritime boundary between Malaysia and Thailand.

Coral reefs in this region are highly exposed to potential impacts of climatic variability originating from the Andaman Sea and the Indian Ocean. Furthermore, the natural landscape of northern Langkawi consists of a combination of rainforest-covered hills rich in vegetation and areas of relatively barren rock formations. The geopark contains one of the most extensive and well-exposed Palaeozoic sedimentary sequences in Malaysia, ranging from the Cambrian to the Permian periods. The Machinchang Cambrian Geoforest Park and Kilim Karst Geoforest Park are among the geoforest parks that preserve both geodiversity and biodiversity across diverse habitats within the study area.

Seabed surface assessment using an acoustic approach

This study used an Acoustic Ground Discrimination System (AGDS), a hydroacoustic remote sensing tool that transmits and receives high-frequency acoustic waves to map marine habitats. According to Foster-Smith & Sotheran [7], the system uses a single-beam echosounder and integrates returned echo components to provide detailed information on seabed characteristics. In addition to depth measurements, the system is capable of quantifying seabed roughness (E1) and hardness (E2).

The E1 and E2 signals are derived from the tail of the first echo and the entirety of the second echo, respectively. White *et al.,* [8] describe the second echo as the signal that is reflected twice before returning to the transducer. Basic data processing and habitat classification rely heavily on the strength of the returned signal (E2). The accuracy of seabed habitat information is therefore dependent on the prevailing seabed conditions during data acquisition.

Hydroacoustic data acquisition was conducted across all nine sampling locations following predetermined transects. Latitude and longitude were recorded using a Differential Global Positioning

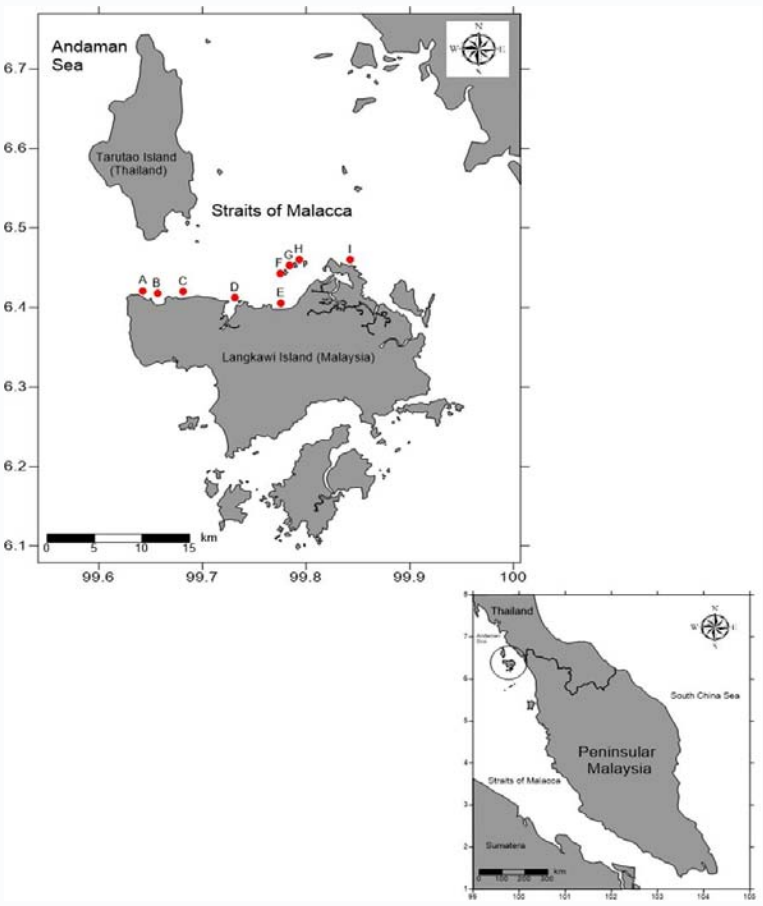


Figure 1: Study area comprising A: Teluk Tanjung Tembun, B: Teluk Datai, C: Teluk Sungai Langgara, D: Pulau Jemuruk, E: Teluk Yu, F: Pulau Dangli, G: Pulau Gasing, H: Pulau Pasir, and I: Teluk Pasir Panjang.

System (DGPS) to ensure precise spatial positioning throughout the mapping process. In waters surrounding smaller islands (Pulau Dangli, Pulau Gasing, and Pulau Pasir), data collection was carried out by circumnavigating the islands in multiple passes, with survey line spacing ranging between 5 and 10 m.

During data acquisition, the recorded signals (coordinates and depth; E1 and E2) were continuously monitored. Areas exhibiting distinct characteristics, such as high E1 and E2 values and variable depths, were carefully observed, along with any anomalous data points. All collected data, stored in American Standard Code for Information Interchange (ASCII) format, were analysed using Surfer 13.0 software to generate thematic maps. The reflection of sound waves generated by the RoxAnn AGDS produces different E1 and E2 values depending on the type of substrate. For example, substrates composed of rock and gravel typically yield high E1 and E2 values. Muddy substrates, on the other hand, absorb sound from the transducer and therefore exhibit very low hardness (E2) and roughness (E1) values due to their relatively smooth and uniform surface. Coral substrates also produce distinctive roughness (E1) and hardness (E2) signatures.

Five classification types were established based on E1 and E2 values, as shown in Table 1. Before seabed data acquisition, the equipment was calibrated using standard reference values for E1 and E2.

Post-Processing of RoxAnn AGDS data

Each dataset was classified according to substrate characteristics by plotting E2 against E1. The accuracy of the classification was determined through visual inspection of data patterns, which is essential for ensuring the reliability of AGDS-based mapping. This approach is referred to as unsupervised classification. The method involves distinguishing areas based on acoustic return signals while avoiding the use of user-defined "box limits" to constrain the data.

Subsequently, the E1, E2, and depth profile data were imported into Surfer software for supervised classification using the Kriging method, while thematic interpolation mapping was performed using the Nearest Neighbour method. For quality control purposes, data with missing or inaccurate values, such as those lacking depth, positional information, or substrate characteristics, were excluded from the analysis.

Table 1: Identified and calibrated marine substrates before data acquisition.

Type of Substrate	E1 Value	E2 Value
Life on a rough surface and dead coral with algae	1.115-2.837	0.067-2.347
Bedrock	1.091-3.187	0.926-2.969
Live corals	0.015-1.209	0.067-0.928
Sands	0.014-2.101	0.068-2.848
Sandy silt and clay	0.002-0.616	0.057-0.432

Results

Depth profile

The depth profile data (Figure 2) show the bathymetric characteristics of the study area. Depth values ranged from 2 m to more than 15 m, forming distinct habitat features that influence the distribution of marine organisms.

Teluk Sungai Langgara, Teluk Yu, and Teluk Pasir Panjang recorded relatively shallow depths ranging from 2 to 5 m. Pulau Jemuruk exhibited a wider depth range of 2 to 15 m. Other study sites, including Teluk Tanjung Tembun, Teluk Datai, Pulau Dangli, Pulau Gasing, and Pulau Pasir, showed depth ranges from 2 m to more than 15 m. The greatest depth recorded was at Pulau Pasir, reaching more than 23 m.

Seabed substrate composition

Figure 3 shows the thematic map of substrate composition in the study area, which was classified into five categories: (i) organisms on rough surfaces and algae-covered dead coral, (ii) live coral cover, (iii) sand, (iv) sandy silt/clay, and (v) rocky substrate.

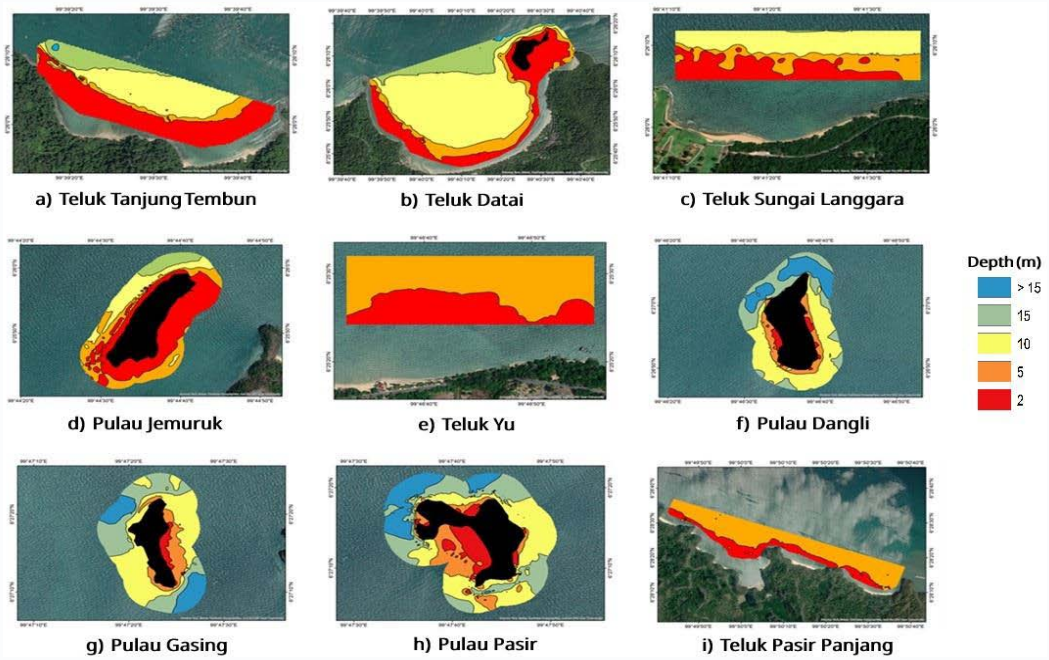


Figure 2: Depth profile for each study site.

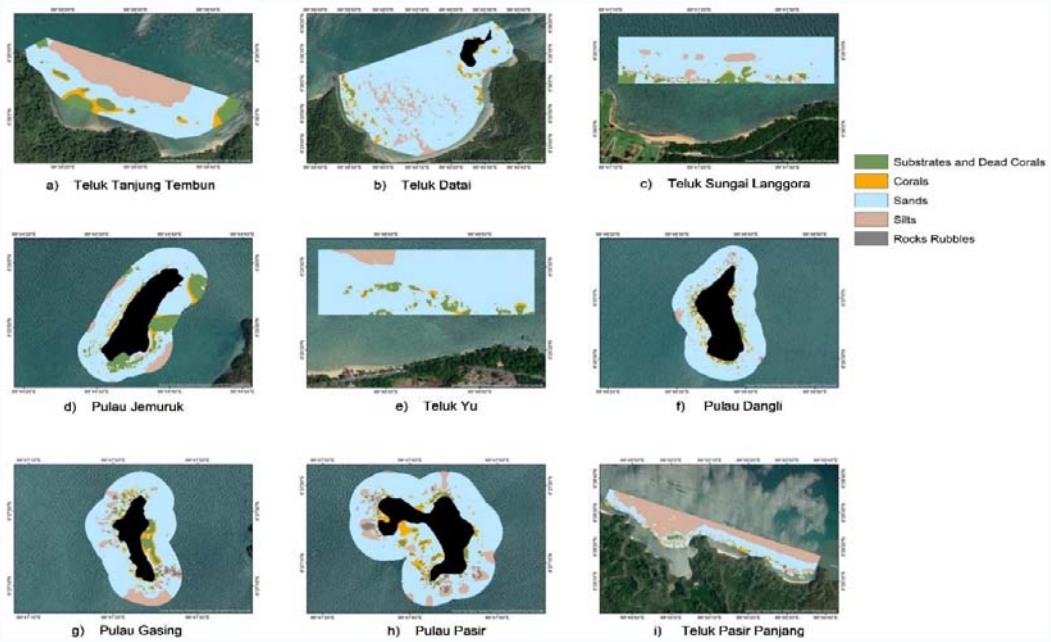


Figure 3: Thematic map of seabed substrate for each study site.

Sand and silt were the most dominant substrate types across all study sites. The presence of organisms on rough surfaces and algae-covered dead coral, as well as live coral, was also recorded at all locations, although generally in moderate to low proportions.

Pulau Pasir recorded the highest live coral cover, with an area of 10,456.99 m^2. Rocky substrates were observed only at Pulau Pasir and Pulau Gasing; the remaining study sites showed no rocky substrate.

Discussion

Currently, a large proportion of marine biological resources, particularly coral reefs, are in a critical state and likely to face future extinction [9]. This situation is driven by increasing levels of degradation and major threats such as overfishing [10], the use of non-selective fishing gear [11, 12], unsustainable coastal development [13], agricultural runoff [14], pollution [15], and high sedimentation rates [16].

Bathymetric profiles provide habitat diversity for marine organisms. In general, shallow coastal waters, particularly along the west coast of Peninsular Malaysia, are dominated by sandy and silty/clay substrates [17]. Variations in depth profiles create suitable habitats for marine species adapted to specific depth and substrate conditions. Understanding depth profiles and substrate composition is essential for effective marine ecosystem management and conservation [18].

Mapping results indicate that coral reefs in the study area are concentrated within a depth range of less than 5 m. For instance, coral reef areas at Pulau Dangli generally occur at depths of 2-5 m. This range lacks reef structural complexity and may be attributed to low water clarity caused by high sedimentation rates. Jonsson [19] reported that water conditions in the study area are characterised by very low visibility and high sediment loads, which is typical of islands located within the Strait of Malacca. This is supported by Lee and Mohamed [20], who reported sedimentation rates in Langkawi of 49.92 mg/cm^2/day and 6.64 mg/cm^2/day for Teluk Yu and Teluk Datai, respectively.

High sedimentation has caused severe siltation problems in several islands along the west coast of Peninsular Malaysia, including Langkawi [21]. Increased sediment loads in Langkawi result from both natural processes and anthropogenic activities such as industrialisation and urbanisation. Activities including construction, agriculture, and tourism contribute to higher sediment inputs into coastal waters, adversely affecting coral reefs and other marine habitats [22, 23].

Fabricius [24] noted that sedimentation levels can significantly reduce coral diversity in such environments. According to Zweifler *et al.,* [25], coral growth in turbid waters, community responses to increased sedimentation, and climate change impacts influence reef development. Studies by Jonsson [19] found that sedimentation significantly affects coral reefs in Langkawi. Reefs near development areas, particularly Pulau Rebak Besar, exhibited the highest levels of coral disturbance and mortality. In contrast, Pulau Singa Besar was identified as the least disturbed site, while Teluk Datai showed moderate levels of disturbance. Despite sedimentation impacts, overall coral diversity was not severely affected.

Field observations indicated that Teluk Sungai Langgara recorded relatively low coral cover compared to other sites, likely due to its proximity to a golf course, which may contribute to coral degradation in the area. A similar result has also been reported by Ismail *et al.,* [2]. Reduced coral diversity is linked to terrestrial pollution and increasing domestic waste inputs associated with tourism activities, which contribute significantly to reef ecosystem decline [26, 27]. In addition, increased sedimentation resulting from monsoonal rainfall runoff exerts prolonged stress on coral communities, leading to accelerated coral degradation [28].

In contrast, Pulau Pasir exhibited higher live coral cover than the other sampling sites, potentially due to the presence of a large sheltered bay on its western side. This bay provides protection from strong wave action and currents, while potentially reducing sedimentation-related stress, thereby creating more stable environmental conditions

that favor coral growth and reef development. Sheltered reef environments are known to support greater coral diversity and resilience by reducing physical disturbances, enhancing juvenile coral survival, and promoting overall reef health [29, 30].

Turbid reefs in northern Langkawi represent unique and understudied ecosystems that play an important role in maintaining coastal biodiversity and ecological balance. Studies have shown that turbid reefs may reduce coral bleaching severity during thermal stress events. A global analysis of 3,694 reef monitoring sites found that higher turbidity reduces bleaching severity during thermal stress events [31].

Raymundo *et al.,* [32] stated that low coral diversity does not necessarily indicate poor reef condition, but rather reflects reduced resilience. Research in Singapore has demonstrated that turbid reefs can support diverse coral communities, with 82 zooxanthellate coral species recorded, including 33 new records. According to Morgan *et al.,* [33], depths between 1 and 5 m, where most of the corals were found in this study, are typically associated with high coral diversity.

Despite their ecological importance, turbid reefs are threatened by coastal development, dredging, and climate change. Effective management strategies are required to ensure their long-term survival. Protecting turbid reef ecosystems is essential for maintaining biodiversity, ecological balance, and their potential contribution to future biomedical discoveries [25, 31].

Conclusion

This study shows that coral reef communities in northern Langkawi are strongly influenced by sedimentation, turbidity, water quality, and local anthropogenic pressures. Coral reefs were mainly distributed at depths of 2-5 m, with differences in coral cover among sites reflecting local habitat conditions. Sheltered areas supported relatively higher live coral cover, whereas sites exposed to greater sedimentation and terrestrial influences showed reduced coral development. Despite these pressures, the turbid reefs of northern Langkawi remain ecologically important and may provide refugia for coral communities under increasing environmental stress. However, continued coastal development, pollution, sedimentation, unsustainable fishing, and climate change pose significant threats to their long-term persistence. Reducing land-based pollution and sediment inputs, promoting sustainable coastal practices, and strengthening long-term reef monitoring are therefore essential to conserve these unique and understudied reef ecosystems.

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Author Contributions

Conceptualization, M.S.I., J.T. and M.N.I.; Data curation, J.T., K.N.A.A. and S.A.K.; Formal analysis, J.T., K.N.A.A., S.A.K., M.S.M.A, and M.N.M.S.; Funding Acquisition, M.S.I. and M.N.I.; Investigation, J.T., K.N.A.A., S.A.K., M.S.M.A, and M.N.M.S.; Methodology, J.T., K.N.A.A. and S.A.K.; Writing-original draft, M.S.I., J.T., K.N.A.A. and S.A.K.; Writing-review and editing, M.S.I.

Ethics Statement

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

Informed Consent Statement

Not applicable.

Data Availability Statement

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

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Declaration of Competing Interests

The authors declare no conflict of interest.

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