Mapping of shallow marine habitats using Sentinel-2A satellite imagery with OBIA method in Tanjung Kelayang coastal area, Belitung Island

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Abstract. Tanjung Kelayang is vulnerable to ecosystem change driven by human activities and environmental factors. This study aimed to map and analyze changes in benthic habitats using Sentinel-2A imagery from 2019 and 2024 by applying an Object-Based Image Analysis (OBIA) approach combined with a Support Vector Machine (SVM) classifier. The analysis included water column correction using the depth-invariant index (DII), multiresolution segmentation, habitat classification, accuracy assessment, and post-classification change detection. Six benthic habitat classes were identified, namely coral, seagrass, macroalgae, sand, rocks, and coral rubble. The results show a decrease in coral cover of 87.99 ha (19.96%) and a substantial increase in coral rubble of 80.33 ha (87.77%), indicating reef degradation. The classification achieved an Overall Accuracy of 70.97% with a kappa coefficient of 0.61, reflecting a good classification performance. These findings demonstrate that Sentinel-2A imagery combined with the OBIA method is effective for monitoring changes in shallow marine habitats, and supports spatial-based coastal zone management.

Keywords: Benthic habitat mapping; habitat change analysis, Object-Based Image Analysis (OBIA), Sentinel-2A, shallow marine habitat

1 Introduction

Indonesia is an archipelagic country with the second-longest coastline in the world, extending approximately 108,000 km [1]. This extensive coastline supports diverse shallow marine ecosystems that provide essential ecological services, including coastal protection, biodiversity maintenance, and fisheries and tourism support. Shallow marine ecosystems are composed of interconnected habitats such as coral reefs, seagrass meadows, macroalgae, and various substrate types including sand, mud, and coral rubble [2]. These habitats serve as

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critical areas for spawning, feeding, and nursery grounds for marine organisms and also function as natural barriers against waves and coastal erosion.

Sustainability of shallow marine ecosystems is closely linked to coastal socioeconomic development. Indonesia's long-term development vision (*Indonesia Emas*) targets an increase in the contribution of the marine sector to national Gross Domestic Product, reaching up to 15% by 2045 [3]. However, shallow marine habitats are highly dynamic and are increasingly threatened by anthropogenic pressures, such as coastal development, tourism activities, and pollution, as well as by natural processes, including tides, waves, and currents. Climate change further exacerbates these pressures through rising sea surface temperatures, which have shown a significant increasing trend across Indonesian waters and pose serious risks to coral reef health and ecosystem stability [4].

Belitung Island, located in Bangka Belitung Province, has extensive coastal and marine areas characterized by diverse shallow marine habitats [5]. Tanjung Kelayang, one of the main coastal tourism destinations on the island, has been designated as a Special Economic Zone and a National Tourism Strategic Area, highlighting its strategic economic importance [6]. Increasing tourism activities in this area may intensify the pressure on shallow marine ecosystems, emphasizing the need for reliable spatial information to support sustainable coastal management.

Remote sensing provides an efficient approach for mapping and monitoring shallow marine habitats over large areas and multiple time periods. Sentinel-2A imagery, with its multispectral capability, high spatial resolution (up to 10 m), and free data accessibility, has been widely applied in coastal and marine environmental monitoring. Advances in digital image analysis, particularly Object-Based Image Analysis (OBIA), have improved the accuracy of benthic habitat mapping by integrating spectral and spatial information. When combined with machine learning algorithms such as support vector machines (SVM), OBIA outperforms conventional pixel-based approaches in complex coastal environments [7].

Despite a growing number of studies applying remote sensing for benthic habitat mapping in Indonesian waters, most existing research has focused on single-date habitat distribution or limited spatial coverage. Comprehensive analyses that integrate object-based classification with multitemporal change detection in strategically important coastal tourism areas remain limited. In particular, long-term assessments of benthic habitat changes in Tanjung Kelayang using consistent satellite data and robust classification methods remain scarce.

Therefore, this study aimed to map and analyze changes in shallow marine benthic habitats in the coastal area of Tanjung Kelayang, Belitung Island, using Sentinel-2A imagery acquired in 2019 and 2024. By applying an Object-Based Image Analysis (OBIA) approach combined with a Support Vector Machine (SVM) classifier, this study sought to provide accurate spatial information on habitat distribution and change dynamics, which can support sustainable coastal management and marine spatial planning in the study area.

2 Materials and methods

The methodological framework of this study was based on satellite data acquisition and object-based image analysis. A detailed description of the study area and the datasets used is presented in the following subsections.

2.1 Study area and data

This study was conducted in the coastal waters of Tanjung Kelayang, Kepayang Island, Babi Kecil Island, and Lengkuas Island (2°32′30″–2°33′30″ S, 107°37′00″–107°41′00″ E), as shown in **Fig. 1.** The analysis utilized Sentinel-2A satellite imagery acquired on April 25, 2019, and March 29, 2024. Field surveys were conducted in October 2024 at 134 sampling locations using the Underwater Photo Transect (UPT) method with an underwater camera and 1 × 1 m quadrat transects. Although there was an approximately seven-month interval between the 2024 satellite image acquisition and the field survey, the field data were used primarily for habitat type identification and classification validation. It was assumed that no major changes in benthic habitat distribution occurred during this short period because benthic habitats generally exhibit relatively slow spatial changes in the absence of extreme disturbance events. Furthermore, no significant environmental disturbances or extreme events that could have substantially altered benthic habitat conditions were reported in the study area during this interval.

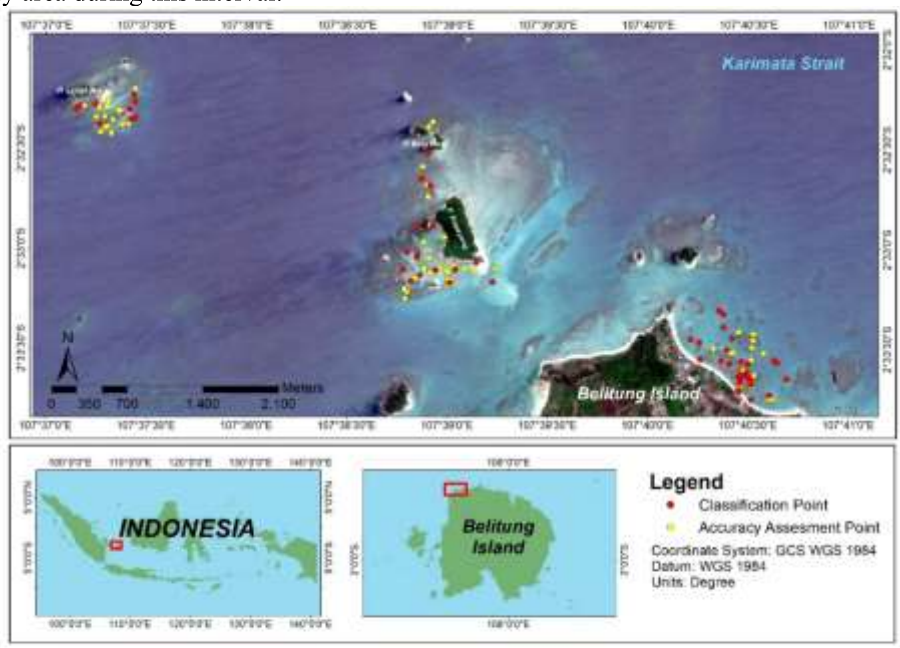

Fig. 1. Location of the study area in the coastal waters of Tanjung Kelayang, Kepayang Island, Babi Kecil Island, and Lengkuas Island.

2.2 Image preprocessing and water column correction

Image preprocessing was the initial stage carried out to enhance the quality of satellite imagery by removing noise and eliminating unnecessary parts from the input image for subsequent processing. The preprocessing steps included cropping, image composition, and atmospheric correction. Following this, water column correction was applied to improve image quality by reducing the effects of water column attenuation, making objects appear clearer, and facilitating object detection within the image [8]. The method used was the Depth Invariant Index (DII), with the following equation [9].

$$DII = ln(L_i) - (k_i/k_j)\, ln(L_j) \quad (1)$$

Where L_i and L_j are the reflectance values of bands i and j, respectively, and k_i/k_j is the attenuation coefficient ratio derived from image statistics.

2.3 Object-based image classification

Object-Based Image Analysis (OBIA) is a remote sensing image analysis approach that classifies image objects rather than individual pixels by integrating spectral, spatial, and contextual information. This approach allows image objects to be defined based on their spectral properties, shape, texture, and spatial relationships, which improves classification performance in complex environments such as shallow marine areas [10]. According to [11], the OBIA classification workflow consists of two main stages: image segmentation and the classification of segmented objects.

Image segmentation is the process of grouping adjacent pixels with similar characteristics into homogeneous objects. In this study, segmentation was performed using the Multiresolution Segmentation (MRS) algorithm, which is controlled by three main parameters: scale, shape, and compactness. The scale parameter determines the size of the image objects, the shape parameter controls the relative influence of spectral information versus object shape, and the compactness parameter regulates the balance between object compactness and smoothness. The multiresolution segmentation was performed using specific parameter settings optimized through iterative testing. At level 1 (reef level), a scale parameter of 60, shape of 0.1, and compactness of 0.5 were applied. At level 2 (benthic level), a scale parameter of 15, shape of 0.1, and compactness of 0.5 were used to delineate finer benthic habitat objects.

The MRS algorithm was applied at two segmentation levels with different scale parameters: level 1 (reef level) to separate land, shallow water, and deep water, and level 2 (benthic level) to delineate benthic habitat distribution. The MRS algorithm is expressed as follows.

$$S_f = w_{colour} . h_{colour} + (1 - w_{colour}) h_{shape} \qquad (2)$$

Where S_f is the segmentation function, w_{colour} is the weight of the color parameter, h_{colour} is the color parameter, and h_{shape} is the weight of the shape parameter.

Image classification was carried out using a machine learning algorithm and 40 ground survey points. The segmentation results served as the basis for classification analysis. The benthic habitat classification scheme was developed based on [12] and was adjusted to the benthic habitats found in the study area, including macroalgae, coral, sand, coral rubble, rock, and seagrass. At level 1, classification was performed using class assignment based on specific threshold values, while level 2 employed the Support Vector Machine (SVM) algorithm. This algorithm worked using training data by identifying an optimal hyperplane that distinguished between two objects and minimized errors during the training phase. The SVM algorithm formula was follows [13]:

$$f(x) = \Sigma_{i \epsilon S} \lambda_i \gamma_i K(x_i x) + w_0 \qquad (3)$$

Where K is the kernel function, γ_i and x_i are training samples, S is the sample corresponding to nonzero Lagrange multipliers, and w_0 is a hyperplane parameter.

2.4 Accuracy assesment

An accuracy assessment was performed to evaluate the reliability of the benthic habitat classification. An error matrix (confusion matrix) was used to compare the classification results with field survey data. Classification accuracy was quantified using Overall Accuracy (OA), producer accuracy (PA), and user accuracy (UA), following Congalton and Green [14]. Overall Accuracy represents the proportion of correctly classified samples relative to the total

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number of reference samples. The producer's accuracy indicates the probability that a reference sample is correctly classified, whereas user accuracy reflects the probability that a classified sample corresponds to its reference class. According to Green et al. [15], an Overall Accuracy greater than 60% is considered acceptable for shallow marine habitat mapping using medium-resolution satellite imagery. OA was calculated using the following equation:

$$OA = \frac{\sum_{i=1}^{k} n_{ii}}{n} \text{ x } 100\% \quad (4)$$

where k is the number of rows in the matrix, n is the number of observations, and n_{ii} is the number of observations in columns i and j.

The kappa coefficient was a statistical measure used to assess the agreement between the two datasets in evaluating the classification accuracy. This value indicates the strength of agreement between the classification results derived from image processing and the actual field conditions [16]. The kappa value ranged from 0 to 1.00, with interpretation categories based on Fleiss [17], as presented in **Table 1**. The kappa coefficient was calculated using the following equation:

$$K = \frac{\sum_{i=1}^{k} n_{ii} - \sum_{i=1}^{k} n_{i+} n_{+i}}{n^2 - \sum_{i=1}^{k} n_{i+} n_{+i}} \quad (5)$$

Where K is the kappa coefficient, n is the number of observations, k is the number of rows in the matrix, n_{ii} is the number of observations in columns i and i, n_{i+} is the marginal total of row i, and n_{+i} is the marginal total of column i.

Table 1. Kappa index categories.

Category	**Kappa index**
Poor	< 0.40
Fair	0.40 – 0.60
Good	0.60 – 0.75
Very good	>0.75

2.5 Change detection

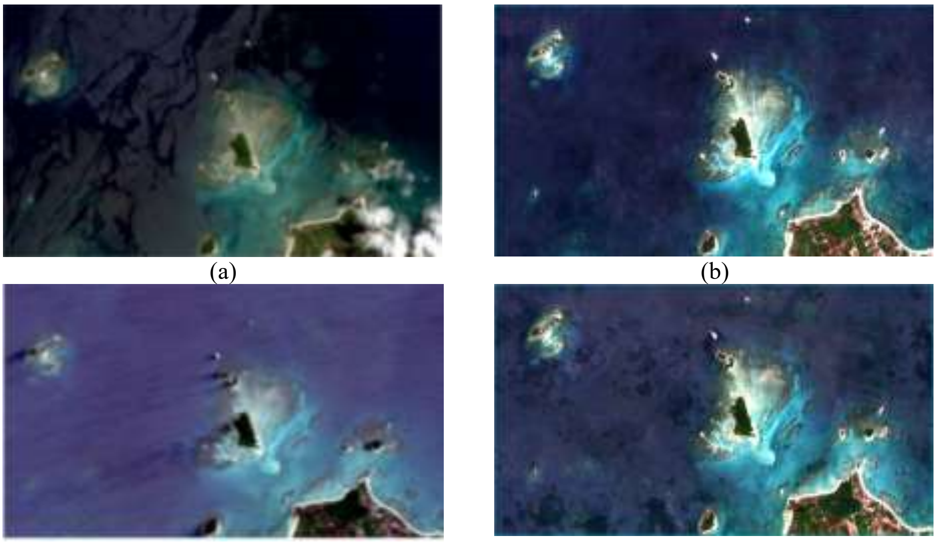
Benthic habitat change was detected using a post-classification comparison method. Two classified images from different years were analyzed using raster-based operations in ArcGIS. To simplify the datasets, features with identical land cover attributes were merged using the dissolve function to remove the internal boundaries. The resulting layers were then overlaid using the intersection function to identify overlapping areas and quantify habitat changes. Although this approach depends on the accuracy of the initial classifications, it is an effective method for detecting changes in the land cover extent and spatial distribution in remote sensing studies [18].

3 Results and discussion

The results obtained using the applied methodological framework are presented and discussed in this section. The analysis began with image preprocessing and water column correction, as these steps are critical for ensuring reliable benthic habitat classification.

3.1 Image preprocessing and water column correction

The preprocessing of Sentinel-2A imagery successfully enhanced the image quality and ensured the reliability of benthic habitat analysis. Atmospheric correction, cloud masking, and spatial cropping effectively reduced atmospheric noise and non-water features, allowing spectral information to better represent the actual water surface conditions, as shown in **Fig. 2**.



(a) (b) (c) (d)

Fig. 2. Visual comparison of Sentinel-2A imagery: (a) original image acquired in 2019, (b) 2019 image after preprocessing, (c) original image acquired in 2024, and (d) 2024 image after preprocessing.

Water column correction using the depth-invariant index (DII) significantly improved the visibility of benthic features at varying depths. The blue band (B2) exhibited a more stable reflectance than the green band (B3), confirming its higher sensitivity to seabed characteristics in shallow waters. The calculated attenuation coefficients were −0.328 for 2019 and −0.315 for 2024, with attenuation ratios (ki/kj) of 0.731 and 0.733, respectively. These values indicate relatively consistent optical properties of water between the two observation periods.

The application of DII enhanced the contrast between benthic substrates, particularly in the deeper reef flat and reef slope areas. Consequently, subsurface objects such as coral, seagrass, and coral rubble became more distinguishable, supporting a more reliable object-based classification. This improvement was critical for minimizing depth-related spectral bias and ensuring that subsequent classification results reflected the actual benthic conditions observed in the field more accurately.

3.2 The result of object-based image classification

The Level 1 classification successfully separated the study area into land, shallow water, and deep water classes, covering a total area of 2,753.8 ha. The shallow water class decreased from 820.5 ha in 2019 to 775.9 ha in 2024, indicating a contraction of shallow marine areas potentially related to sediment dynamics or coastal processes. This shallow water zone served as the spatial boundary for level 2 classification, which focused on benthic habitat mapping.

At Level 2, six benthic habitat classes were identified: coral, coral rubble, seagrass, macroalgae, sand, and rock. The spatial distributions of these habitats exhibited clear geomorphological patterns. Sand was predominantly distributed along the coastline, reflecting high-energy nearshore environments. Macroalgae were extensively found on the eastern side of Tanjung Kelayang, and were likely influenced by nutrient availability and hydrodynamic conditions. Coral habitats were mainly concentrated along the reef slope, whereas coral rubble dominated the inner reef flat, suggesting ongoing reef degradation processes. Seagrass was scattered in relatively sheltered and concave reef flat areas, whereas rock habitats were limited to zones closest to the mainland and around small islands, such as Lengkuas, Kepayang, Tukong Aji, and Babi Kecil.

A comparative analysis between 2019 and 2024 indicated noticeable spatial shifts among benthic habitat classes, particularly those involving coral-related substrates. These distribution patterns highlight the dynamic nature of the shallow marine ecosystems in Tanjung Kelayang and emphasize the sensitivity of coral reef environments to both natural processes and anthropogenic pressures. The classification results are presented in **Fig. 3** and **Fig. 4**.

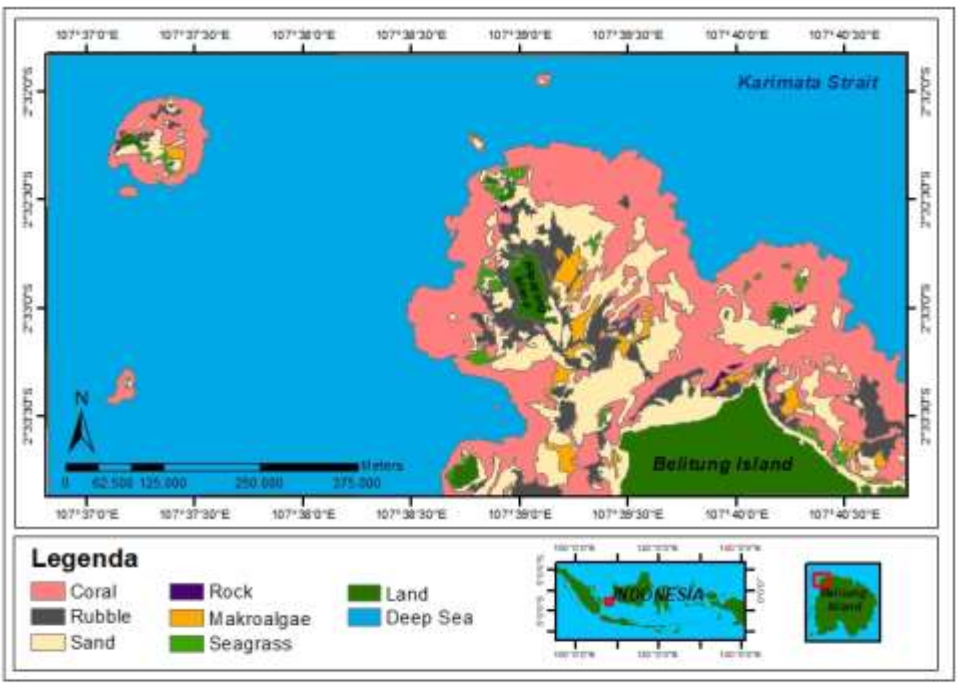


Fig. 3. Level-2 shallow marine habitat map in the coastal area of Tanjung Kelayang, Belitung Island, Kepayang Island, Babi Kecil Island, and Lengkuas Island based on 2019 image acquisition.

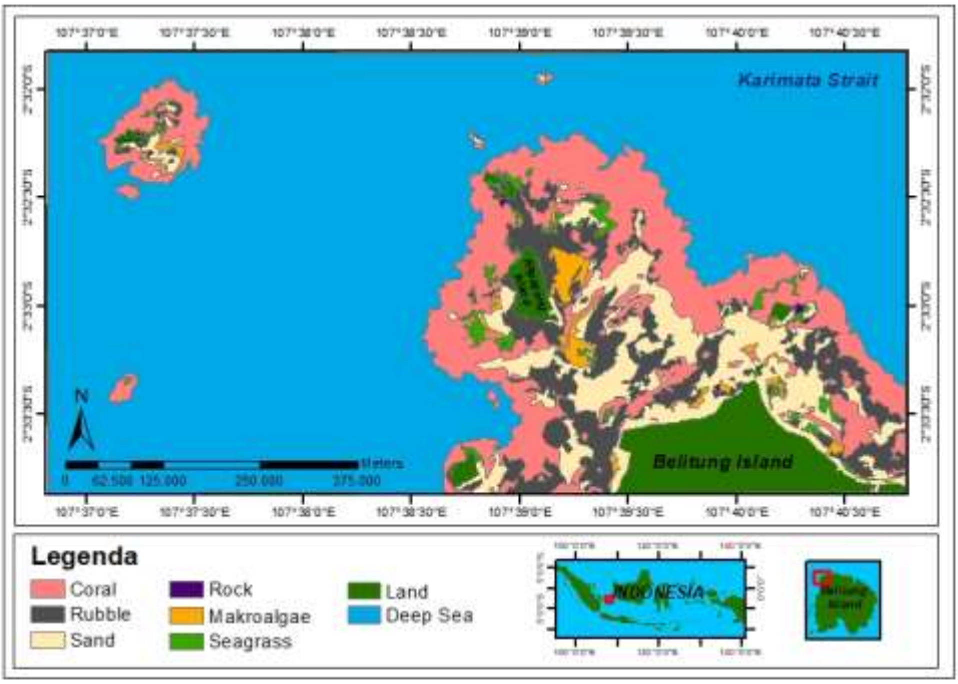


Fig. 4. Level-2 shallow marine habitat map in the coastal area of Tanjung Kelayang, Belitung Island, Kepayang Island, Babi Kecil Island, and Lengkuas Island based on 2024 image acquisition.

The field survey findings were consistent with those of [19], who stated that corals were generally found on the reef slope, coral rubble on the reef crest, and seagrass in shallow lagoons filled with fine sand. The distribution of benthic habitats in Tanjung Kelayang is influenced by depth, substrate type, and local oceanographic dynamics. Information regarding the distribution of benthic habitats in the study area is presented in **Table 2**.

Table 2. Area of benthic habitat classes and their changes in the coastal area of Tanjung Kelayang, Belitung Island, Kepayang Island, Babi Kecil Island, and Lengkuas Island.

Benthic Habitat Class	Area (ha)		Change in Area (ha)	Percentage Change (%)
	2019 Imagery	2024 Imagery	2019 – 2024 Imagery	2019 – 2024 Imagery
MA	31,30	26,58	- 4,72	15,07
S	235,36	194,51	- 40,85	17,36
C	440,80	352,81	- 87,99	19,96
R	91,52	171,85	80,33	87,77
RCK	2,81	2,82	0,0007	0,02
SG	18,25	27,29	9,04	49,54

Legend: Macroalgae (MA), sand (S), mixed dead and live coral (C), rubble (R), rock (RCK), and seagrass (SG)

Table 2 presents data on the area changes of each benthic habitat class in the study area during 2019–2024. To clarify the trend of these changes, the data were visualized in a graph in **Fig. 5**, making it easier to observe the patterns of increase or decrease in each habitat class.

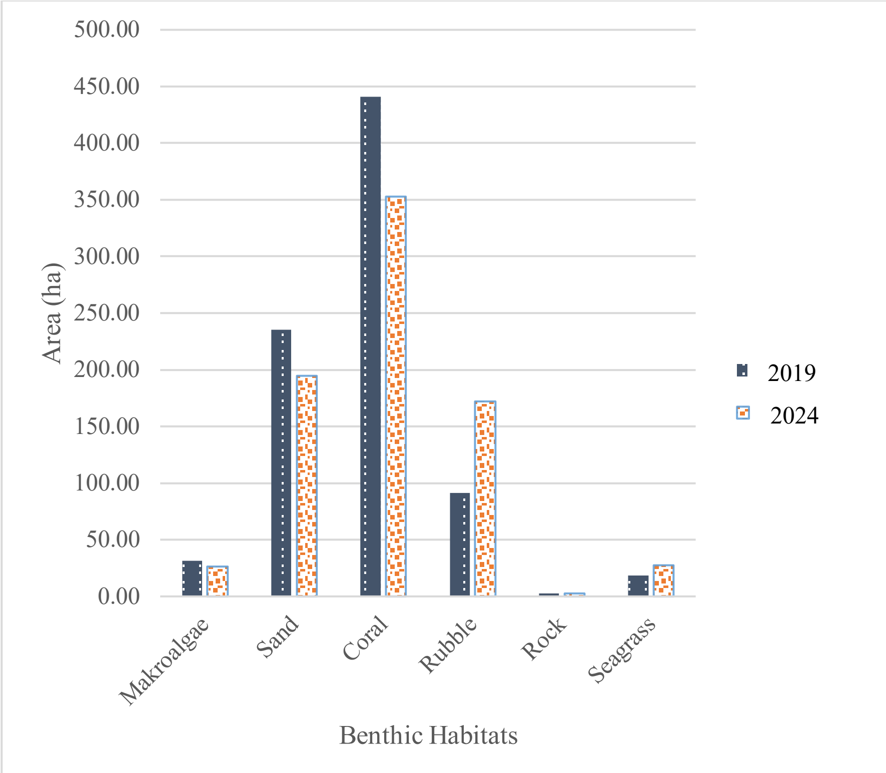


Fig. 5. Graph showing the area of benthic habitat classes and their changes in the coastal region of Tanjung Kelayang, Belitung Island, Kepayang Island, Babi Kecil Island, and Lengkuas Island based on 2024 image acquisition.

Fig. 5 shows that the coral class dominated the shallow marine area of Tanjung Kelayang and its surrounding waters, however, it experienced a decrease of 87.99 ha (19.96%) over the five-year period. In contrast, the coral rubble class increased by 80.33 ha (87.77%), indicating substantial reef degradation, which is likely associated with a combination of global warming and anthropogenic pressures. The expansion of the seagrass area suggests an adaptive response of the ecosystem to environmental disturbance, whereas the rock class remained relatively stable, exhibiting minimal spatial change.

3.3 Accuracy assessment

An accuracy assessment was conducted using the confusion matrix method with 93 test points (70% of the field data), which were different from those used for classification. The classification results from the 2024 imagery showed an Overall Accuracy (OA) of 70.97% and kappa coefficient of 0.61, which fell into the good category. The highest producer accuracy (PA) and user accuracy (UA) values were found in the rock class (100%), while the lowest values were observed in the seagrass class (42.86% and 50%, respectively). Low accuracy was influenced by an imbalanced sample distribution across classes, differences in conditions between image acquisition and field survey time, and the complexity of benthic habitats. The kappa value indicated that the classification had a fairly good level of agreement considering the possibility of random classification errors.

3.4 Analysis of benthic habitat changes

Benthic habitat change detection was conducted using a post-classification comparison method between the classified images from 2019 and 2024. This method allowed for the specific identification of changes between habitat classes, and produced new classes that represented transitions between different cover types. These changes reflect the ecosystem dynamics influenced by both natural factors and human activities. The visualized results of these changes are shown in **Fig. 6.**

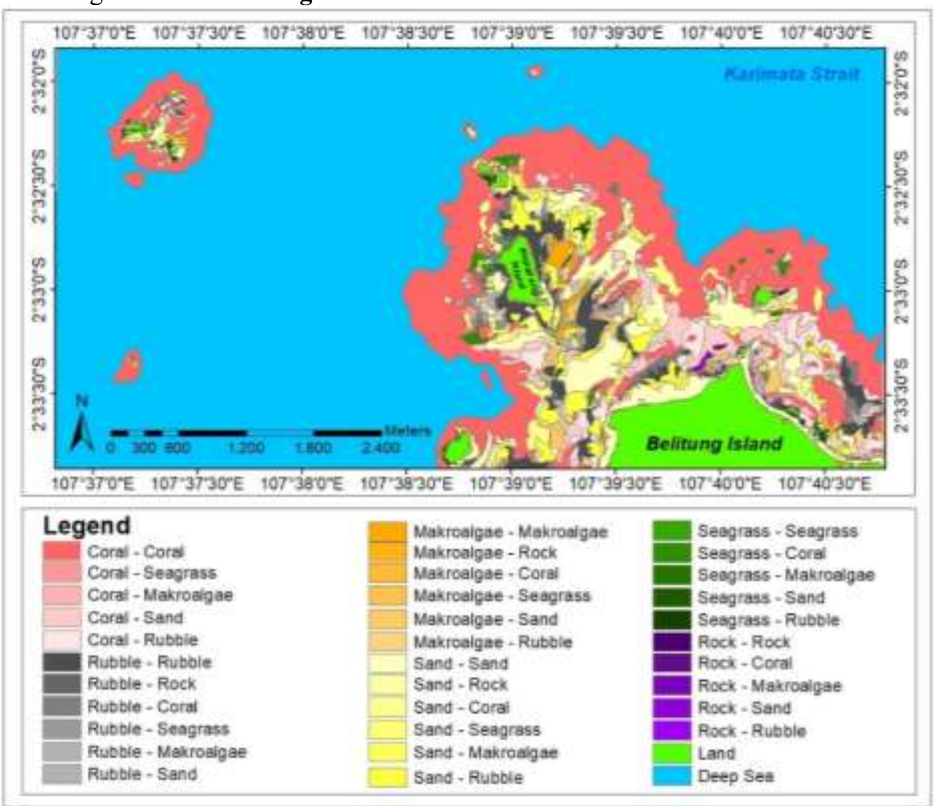


Fig. 6. Map of shallow marine habitat changes in the coastal area of Tanjung Kelayang, Kepayang Island, Babi Kecil Island, and Lengkuas Island from 2019 to 2024.

Fig. 6 shows the 35 classified habitat categories representing both unchanged and altered benthic habitats. Each transition between habitat classes was displayed using different color gradients specific to each class: pink for coral, green for seagrass, orange for macroalgae, cream for sand, purple for rock, and grey for coral rubble. Statistical information on changes in habitat area is presented in **Fig. 7**.

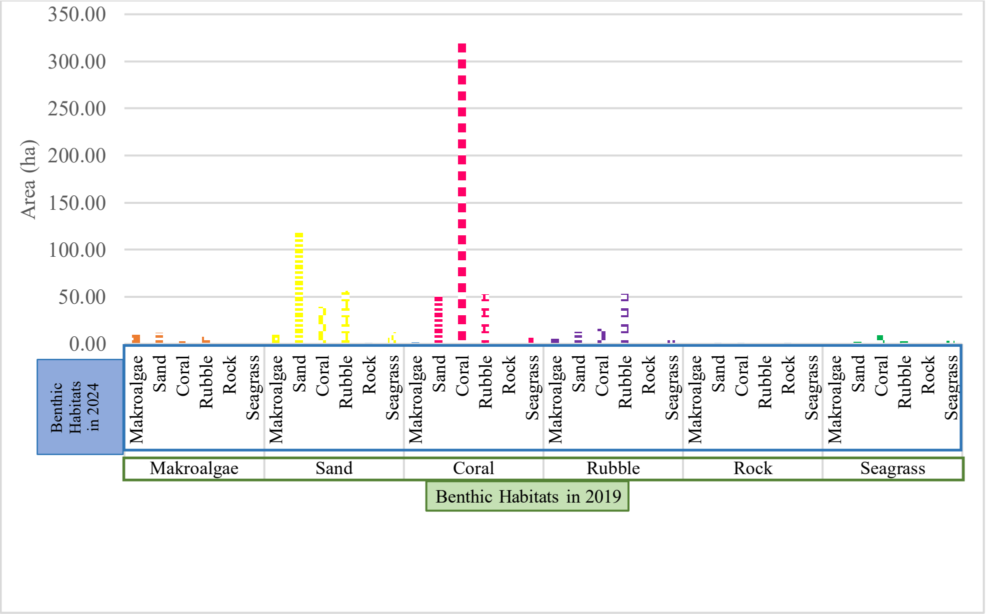


Fig. 7. Changes in benthic habitat in the coastal areas of Tanjung Kelayang, Kepayang Island, Babi Kecil Island, and Lengkuas Island from 2019 to 2024.

Based on **Fig. 7,** changes in benthic habitats along the coast of Tanjung Kelayang over the past five years reflect a dynamic balance between habitat stability and degradation. The rock class exhibited the least change, which could be attributed to its inherently stable physical characteristics. Minor changes were also observed in seagrass and macroalgal habitats. The dominant seagrass species, *Thalassia hemprichii* showed a relatively low average cover across the study area, indicating limited spatial expansion during the observation period. In contrast, substantial changes were observed in the coral-related habitats.

Significant transitions were detected from sand to coral rubble, covering 56.3 ha, and from live coral to coral rubble, covering 52.9 ha. The conversion of sand to coral rubble is likely associated with the accumulation of coral fragments originating from the surrounding reef areas. These fragments were potentially generated by reef fragmentation caused by high-energy storm events or coral mortality upstream, and subsequently transported by coastal currents.

The conversion of 52.9 ha of coral into coral rubble provided strong evidence of coral reef degradation in the study area. This degradation was likely driven by multiple environmental stressors, including mass coral bleaching associated with increasing sea surface temperatures and extreme storm events that physically damaged the reef structures. [20] reported that the average monthly sea surface temperatures in Indonesian waters have increased by approximately 0.0003°C, with a significant rise of 0.14°C per month over the past 15 years. In addition to natural stressors, anthropogenic pressures such as destructive fishing practices and coastal pollution may further exacerbate coral fragmentation. These findings highlight the importance of continuous monitoring, regulation of human activities, and implementation of reef restoration measures, such as coral transplantation, to support the recovery and long-term sustainability of shallow marine ecosystems on Belitung Island and surrounding small islands.

4 Conclusion

This study aimed to map and analyze changes in shallow-water benthic habitats in the coastal area of Tanjung Kelayang using Sentinel-2A imagery and OBIA. The results successfully identified six benthic habitat classes, and revealed notable habitat dynamics between 2019 and 2024. Significant reductions in coral and sand areas were observed, primarily transitioning into coral rubble, indicating ongoing reef degradation, whereas rock habitats showed minimal changes. These findings demonstrate that OBIA with the Sentinel-2A framework is effective for monitoring benthic habitat changes and provides valuable spatial information to support coastal ecosystem management.

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