Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 29(6): 1545 – 1556 (2025)
www.ejabf.journals.ekb.eg

High-Resolution Benthic Habitat Mapping Using Planet Scope Imagery: A Case Study of Tikus Island, Bengkulu Province, Indonesia

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ARTICLE INFO

Article History:
Received: Aug. 2, 2025
Accepted: Nov. 5, 2025
Online: Dec. 2, 2025

Keywords:
Benthic habitat mapping,
Shallow water habitat,
Planet Scope imagery,
High spatial resolution,
Tikus Island

ABSTRACT

This study aims to produce a high-resolution benthic habitat map of Tikus Island using Planet Scope satellite imagery supported by field observations. High-resolution mapping is essential for characterizing shallow-water ecosystems, especially on small islands where habitat conditions vary at fine spatial scales. Small-island reef systems often contain narrow reef flats, patchy coral heads, and abrupt substrate transitions that occur at scales of only a few meters. These features tend to be lost or merged at medium spatial resolutions, so higher-resolution imagery is especially valuable for capturing the fine spatial variability that characterizes these environments. Planet Scope Level 3B imagery acquired on 20 September 2020 was processed to improve visibility and minimize surface effects before classification. Field data were collected through the Underwater Photo Transect method in November 2022, resulting in 270 georeferenced photos used to identify major habitat types. These data served as training and validation inputs for a pixel-based Maximum Likelihood Classification to distinguish six benthic habitat classes: live coral, dead coral, rubble, sand, macroalgae, and rock. The classification showed that live coral forms the largest habitat, covering 119.6 ha (37%). Rubble occupied 65.9 ha (24%), followed by dead coral at 34.9 ha (11%). Sand covered 25.9 ha (8%), macroalgae 14.4 ha (6%), and rock 0.3 ha (3%). Overall accuracy reached 75.51%, with a Kappa coefficient of 0.69, indicating strong agreement between image-based classification and field observations. Misclassification occurred mainly among macroalgae, rock, and dead coral due to similar reflectance patterns in shallow water. These findings demonstrate that Planet Scope imagery provides reliable, high-resolution information for benthic habitat assessment in small-island environments. The resulting habitat map offers a detailed baseline for monitoring reef condition and supports management efforts aimed at protecting coastal ecosystems in Bengkulu Province.

INTRODUCTION

Tikus Island lies off the western coast of Sumatra and faces the Indian Ocean. It is the only small island governed by Bengkulu City and lies about ten kilometres offshore, approximately thirty minutes by boat. The surrounding waters contain an extensive coral reef system that supports diverse fish and invertebrate communities. Earlier assessments estimate that these reefs cover around 238 hectares, making them one of the most significant shallow-water ecosystems in the province. These habitats serve as feeding and nursery grounds, stabilize coastal sediments, protect shorelines from wave energy, and support economic activities such as fisheries and tourism **(Mastu *et al.*, 2018; Sugara *et al.*, 2022)**. Because of their ecological and socioeconomic importance, accurate spatial information on benthic habitat distribution is vital for monitoring environmental conditions and managing coastal resources effectively.

Shallow-water ecosystems are sensitive to both natural and human-induced pressures, including storms, sedimentation, pollution, and coastal development. Traditional field surveys provide detailed observations but are limited in spatial coverage and require considerable time and resources. As a result, satellite remote sensing has become an essential tool for characterizing benthic environments. It provides broad coverage, repeat observations, and long-term monitoring capabilities that are increasingly important for regions experiencing rapid coastal change. The ability of remote sensing to detect habitat variation, assess reef condition, and support conservation depends largely on image resolution and the suitability of processing techniques.

Previous studies around Tikus Island used medium-resolution imagery, particularly Landsat 8, to classify benthic habitats. While these studies produced valuable baseline information, the 30-meter spatial resolution restricted the detection of small coral patches, narrow reef edges, and mixed substrates commonly found in shallow tropical waters **(Anggoro *et al.*, 2020)**. No high-resolution satellite analysis has yet been conducted for Tikus Island, leaving a gap in understanding its fine-scale habitat structure. This is important because the island faces the open Indian Ocean, where strong waves and currents create complex habitat patterns that require higher-resolution mapping to interpret accurately.

Planet Scope imagery offers the capability to address this gap. With a spatial resolution of approximately three meters and daily revisit frequency, Planet Scope can capture habitat details that medium-resolution sensors cannot. Its high temporal availability also allows selection of scenes with minimal cloud cover and favorable water conditions, improving reliability for shallow-water mapping **(Darweesh *et al.*, 2021)**. Compared with sensors such as Sentinel-2 or Landsat, Planet Scope provides finer spatial detail at a frequency more suitable for regions where environmental conditions vary quickly. This balance of resolution and availability makes it especially useful for small-island ecosystems.

Studies in other coral reef regions have demonstrated that higher-resolution imagery substantially improves benthic classification by allowing clearer separation of habitat types and reducing confusion between substrates that exhibit similar reflectance patterns at coarser resolutions. Applying this approach to Tikus Island provides an opportunity to generate more accurate habitat information and support long-term ecosystem monitoring in Bengkulu Province.

In response to these needs, this study uses Planet Scope imagery to map shallow-water benthic habitats around Tikus Island. The objectives are to (1) classify major benthic habitat types using high-resolution satellite imagery, (2) assess classification accuracy with field-based observations, and (3) evaluate the potential of Planet Scope as a tool for supporting coastal monitoring and management in Bengkulu Province.

MATERIALS AND METHODS

1. Study area

The study was carried out in the shallow-water habitats surrounding Tikus Island, located in the 48S UTM zone off the western coast of Bengkulu Province. The island lies approximately 10km offshore and is directly exposed to the Indian Ocean, resulting in strong wave energy, high water movement, and considerable variation in benthic structure. These dynamic conditions create a mosaic of habitat types that make the island well suited for testing high-resolution mapping approaches. A Planet Scope Level 3B satellite image acquired on 20 September 2020 served as the primary dataset. This imagery provides multispectral data with a spatial resolution appropriate for detecting fine-scale habitat patterns.

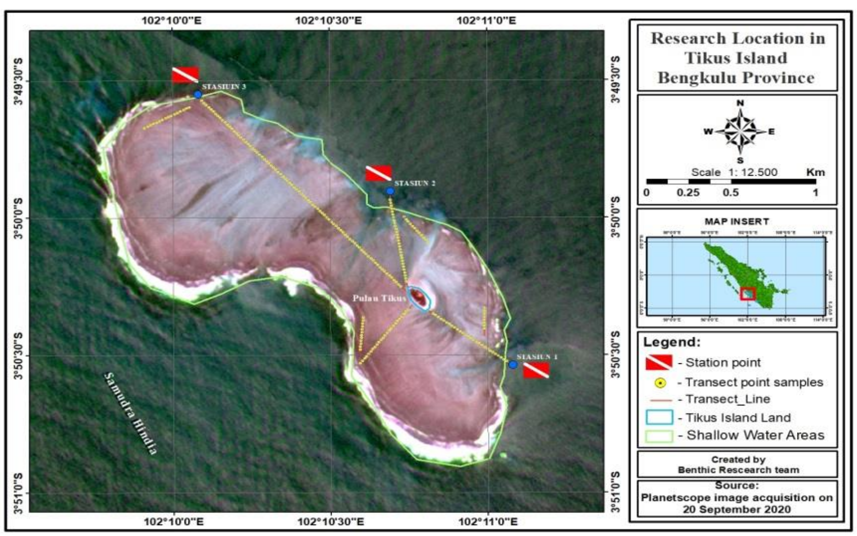

Fig. 1. Study area map showing the location of Tikus Island, including the scale bar, north arrow, and UTM grid coordinates

2. Field data collection

Field observations were collected using the Underwater Photo Transect (UPT) method, which provides georeferenced visual documentation of benthic conditions. Systematic random sampling was used to capture habitat variability throughout the shallow reef zone. Transects were placed perpendicular to the reef edge to record transitions from reef crest to lagoonal substrates. Each transect used a 3 × 3 m frame containing two internal quadrats of 0.75 × 0.75 m (Fig. 2). Underwater photographs were taken at 3-meter intervals to ensure consistent coverage.

A total of 270 photographs were collected from 135 field stations at depths ranging from 1 to 7 meters. These depths captured reef flats, rubble fields, and shallow sandy substrates. Transect start and end points were georeferenced with a handheld GPS receiver, and divers maintained bearing alignment using underwater compasses to match the satellite footprint. The photographs were analyzed in CPCe to identify dominant benthic categories live coral, dead coral, rubble, sand, and macroalgae. Each photo was interpreted in CPCe using a set of randomly distributed points, which were assigned to the dominant benthic category. This point-based approach reduces interpreter bias and provides consistent input for training and validation. These classifications served as the ground-truth dataset for training and validating the satellite-derived habitat map.

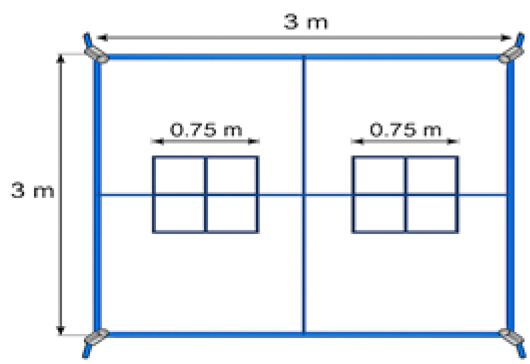

Fig. 2. Transect layout used for underwater photo sampling, showing the 3 × 3m frame and internal 0.75 × 0.75m quadrats, with grid dimensions indicated for reference

3. Satellite data and pre-processing

The PlanetScope Level 3B image used in this study has a nominal ground sampling distance of 3m, which corresponds to the resolution of the Dove-R spacecraft constellation from which the 20 September 2020 scene was acquired. The fine spatial detail enables detection of small coral patches, narrow reef boundaries, and mixed substrates that medium-resolution sensors such as Sentinel-2 (10m) or Landsat (30m) cannot resolve. While very-high-resolution sensors like WorldView offer sub-meter resolution, their limited temporal availability and higher cost make them less suitable for routine monitoring of remote small islands.

Image pre-processing was conducted using ENVI 5.x and QGIS 3.x. Sunglint correction was applied using the method developed by **Tiskus *et al.* (2023)**, which uses the relationship between visible and near-infrared bands to reduce the influence of wave-induced surface reflection. This step enhances the visibility of benthic features in shallow water. The image was then cropped to the shallow-water area surrounding Tikus Island to focus processing efforts and remove irrelevant deep-water zones.

Water-column correction was performed using the depth-invariant index (DII) technique based on Lyzenga’s algorithm. This approach normalizes reflectance across band pairs to reduce depth-related attenuation **(Rachmawati *et al.*, 2018)**. After correction, a mask was applied to exclude deep-water pixels and terrestrial features, retaining only the shallow benthic zone for classification.

4. Classification and accuracy assessment

Benthic habitat classification was conducted using the Maximum Likelihood Classification (MLC) algorithm, a supervised method that assigns each pixel to the class for which it has the highest statistical probability. Training data were derived from the CPCe-analyzed UPT photographs. Of the 270 images, 70% were allocated for classifier training and 30% for validation.

Six habitat classes were defined based on field observations: live coral, dead coral, rubble, sand, macroalgae, and rock. These categories represent the dominant benthic types found around Tikus Island and are commonly used in shallow-water mapping studies.

Classification accuracy was evaluated using a confusion matrix that compared the classified habitat map with the independent validation dataset **(Green *et al.*, 2000)**. The matrix provided overall accuracy (OA), producer’s accuracy, user’s accuracy, and the Kappa coefficient. An OA value above 70% and a Kappa coefficient greater than 0.6 were considered acceptable indicators of classification reliability, consistent with standards used in benthic habitat studies.

RESULTS

The classification of Planet Scope Level 3B imagery produced a detailed benthic habitat map for the shallow-water areas surrounding Tikus Island (Fig. 3). Six major habitat classes were identified across the study area: live coral, dead coral, rubble, sand, macroalgae, and rock. These classes reflect the dominant substrates and biological assemblages observed during the field survey and captured by the satellite imagery.

The spatial analysis indicated that live coral constituted the largest habitat category, covering 119.6 hectares, or approximately 37% of the mapped area. This class was distributed primarily along the shallow reef zones, where branching, encrusting, and foliose coral forms were observed during the field campaign. Rubble formed the second most extensive category, occupying 65.9 hectares, equivalent to 24% of the total area. Rubble was widely distributed and appeared in both isolated patches and continuous stretches, often in proximity to live coral zones.

Dead coral accounted for 34.9 hectares, representing around 11% of the mapped habitat. These areas were characterized by structurally intact but non-living coral frameworks, which were also confirmed in the underwater photographs. Sand substrates covered 25.9 hectares, or 8% of the study area, and were typically located in lagoonal sections and between coral structures. Macroalgae occupied 14.4 hectares (6%), appearing mainly on the southern portion of the island. The smallest class was rock, which covered 0.3 hectares (3%), and was distributed sparsely across the reef flats.

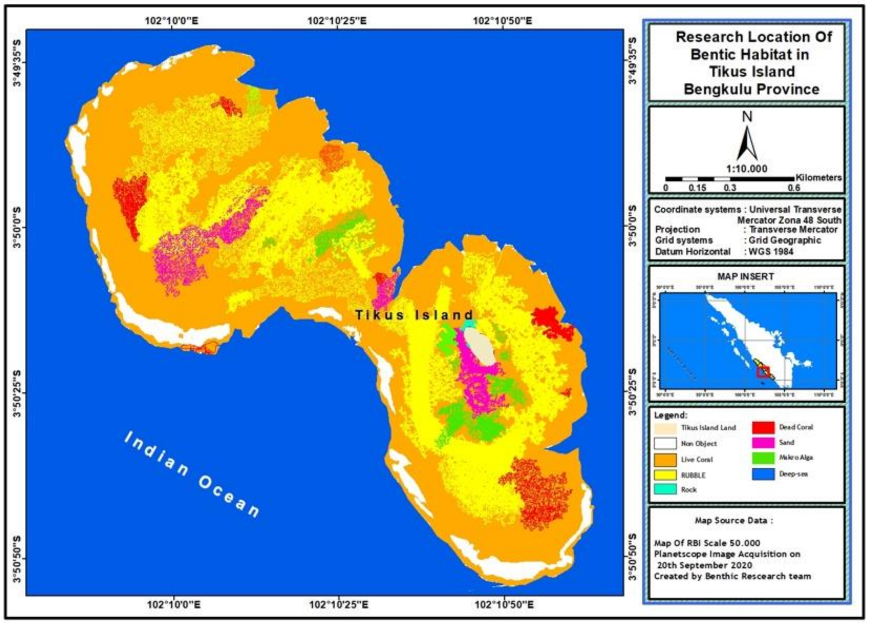

Fig. 3. Benthic habitat map of Tikus Island derived from Planet Scope Level 3B imagery

The classification accuracy assessment demonstrated that the mapped habitats corresponded closely with field observations. A total of 49 validation samples were used to evaluate accuracy, resulting in an overall accuracy (OA) of 75.51% and a Kappa coefficient of 0.69. These values indicate a strong level of agreement between the classified map and the reference data.

User's accuracy (UA) values varied among habitat classes. Live coral achieved the highest UA at 93%, indicating that most pixels classified as live coral matched the corresponding field labels. Sand exhibited a UA of 71%, while macroalgae and rock each produced UA values of 67%. Dead coral achieved a UA of 70%, and rubble obtained a UA of 64%. These accuracy values reflect the classifier's ability to correctly label pixels for each category based on training data.

Producer's accuracy (PA) also varied across habitat classes. Live coral, dead coral, and rubble each achieved PA values of 100%, meaning that all field-observed samples belonging to these classes were correctly identified in the classification. In contrast, macrosalgae and rock recorded lower PA values, at 29% and 28% respectively. Sand achieved a PA value of 71%. The lower PA values for macroalgae and rock reflect their limited spectral separability from adjacent classes such as dead coral or rubble, as observed in the validation dataset.

The distribution of UA and PA values for each habitat class is summarized graphically in Fig. (4). The figure illustrates the relative performance of the classification for individual benthic categories, highlighting the strong agreement for live coral, dead coral, and rubble, and more moderate agreement for macroalgae and rock.

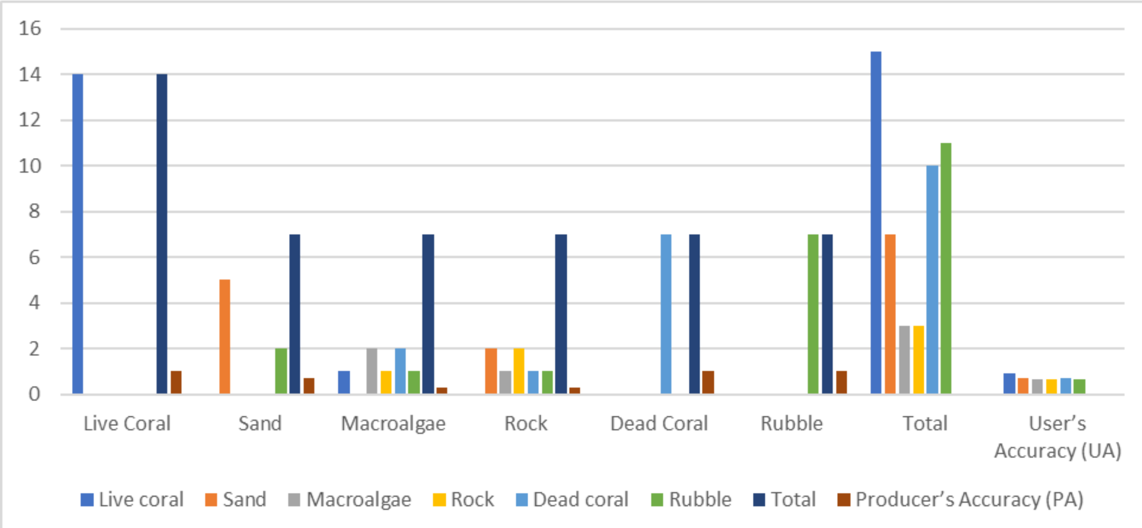

Fig. 4. User's and producer's accuracy for each benthic habitat class

The numerical details of the accuracy results are further presented in Table (1), which displays the confusion matrix constructed from the validation dataset. The matrix contains counts of correctly and incorrectly classified pixels for each habitat class, as well as corresponding UA and PA values. The data in Table (1) show that 14 validation samples of live coral were correctly classified, with only one misclassification. Sand exhibited two misclassifications into the rock class. Macroalgae displayed one misclassification each into dead coral, rock, and rubble. Rock had one misclassification into macroalgae. Dead coral was misclassified twice into macroalgae and once into rock. Rubble showed misclassification into sand, macroalgae, and rock.

Table 1. Confusion matrix and accuracy assessment for the classified benthic habitat map

Classified Pixels	**Live Coral**	**Sand**	**Macroalgae**	**Rock**	**Dead Coral**	**Rubble**	**Total**	**UA**
Live coral	14	0	1	0	0	0	15	93%
Sand	0	5	0	2	0	0	7	71%
Macroalgae	0	0	2	1	0	0	3	67%

Rock	0	0	1	2	0	0	3	67%
Dead coral	0	0	2	1	7	0	10	70%
Rubble	0	2	1	1	0	7	11	64%
Total	14	7	7	7	7	7	—	—
PA	100%	71%	29%	28%	100%	100%	—	

Overall accuracy (OA): 75.51%, Kappa coefficient: 0.69.

The confusion matrix confirms the high reliability of the classification for live coral, dead coral, and rubble. In addition, it highlights moderate performance in distinguishing macroalgae and rock, which displayed both lower UA and PA values. These variations in performance reflect spectral overlap among closely related substrate types, particularly in optically shallow environments with mixed benthic cover.

The final benthic habitat map (Fig. 3) provides a complete spatial representation of the six classes across the study area. The distribution patterns correspond closely with field observations and illustrate the extent of each habitat type around Tikus Island. Together, the mapped classes, calculated areas, and validated accuracy metrics provide a comprehensive depiction of the benthic environment as derived from Planet Scope imagery.

DISCUSSION

1. Interpretation of benthic habitat patterns

The benthic habitat map derived from Planet Scope imagery reveals clear spatial patterns around Tikus Island. The substantial extent of live coral indicates that portions of the reef remain structurally intact, supporting healthy biological communities. Field observations noted a mixture of branching, encrusting, and foliose coral forms, suggesting that habitat complexity is still present and capable of sustaining diverse reef organisms **(Nguyen *et al.*, 2023)**. The presence of these coral morphotypes implies ongoing reef growth and potential resilience despite exposure to strong wave action from the Indian Ocean.

Rubble showed a wide distribution across the survey area, reflecting physical disturbances that may have occurred in the past. Rubble often accumulates in areas exposed to high hydrodynamic energy or where coral skeletons have fractured over time. Its coexistence with sand and macroalgae suggests active substrate turnover, where erosion, transport, and biological colonization interact. While rubble can limit coral recruitment in some zones, its mosaic distribution alongside healthy coral areas may reflect a system experiencing both degradation and natural recovery.

Macroalgae were concentrated in the southern portion of the island. This pattern likely relates to local environmental conditions such as nutrient availability, shading, or water movement **(El-Sadek *et al.,* 2022)**. Macroalgae frequently occupy spaces created by coral mortality or disturbance, and their distribution may also indicate competitive interactions that shape habitat transitions.

2. Comparison with previous studies

Earlier mapping conducted with medium-resolution Landsat imagery provided a general overview of benthic habitats but was unable to capture the fine-scale variation present around Tikus Island **(Anggoro, 2015)**. The improved spatial detail in the present study is directly linked to Planet Scope’s 3–5 m resolution, which resolves narrow reef edges, small coral heads, and mixed substrates that were previously aggregated into broader classes. This high-resolution dataset therefore yields a more realistic representation of shallow-water habitats, highlighting the benefits of applying finer spatial resolution for small-island reef systems.

3. Ecological implications of habitat distribution

The predominance of live coral across shallow sections of the reef suggests that key ecological functions such as habitat provisioning, shoreline protection, and carbonate production are still active. This distribution may reflect reef resilience in certain areas, where coral communities continue to thrive despite environmental pressures. In contrast, widespread rubble indicates zones of potential structural degradation, highlighting areas where storm damage, bioerosion, or other disturbances may have influenced reef condition.

The spatial arrangement of macroalgae may also hold ecological significance. Concentrations of macroalgae can signal nutrient enrichment, reduced herbivory, or recent disturbance. Their presence, especially near rubble fields, may reflect transitional conditions where communities are shifting between coral dominance and algal influence. While these spatial patterns help illustrate ecological processes operating across the reef, they also point to several analytical difficulties encountered during classification. Many of the transitions between habitats occur over very short distances, which increases the likelihood of spectral mixing and limits separability among certain classes. These ecological gradients therefore connect directly to the classification challenges discussed in the following section.

4. Classification challenges and spectral limitations

Distinguishing among certain benthic classes presented challenges, particularly for macroalgae and rock. These classes exhibited lower producer’s accuracy due to their spectral similarity and frequent co-occurrence with other substrates. Macroalgae often overlap or intermingle with dead coral or rubble, producing mixed spectral signatures that complicate detection. Similarly, rock and dead coral have comparable reflectance properties in optically shallow waters, especially where depth changes rapidly or where water clarity is variable.

Depth variability further complicates classification. Although water-column correction reduces attenuation effects, residual depth influence can remain, making it difficult to differentiate classes that share similar spectral characteristics. This effect is pronounced around Tikus Island, where depth transitions occur abruptly along the reef slope.

5. Methodological and environmental limitations

Several factors may have influenced classification reliability. The temporal mismatch between the satellite imagery and the field survey introduces the possibility that actual environmental change contributed to discrepancies between field observations and classified outputs. Habitat types such as live coral and macroalgae can change in response to storms, bleaching events, sedimentation, or natural succession.

Environmental conditions at the time of image acquisition may also have affected classification accuracy. Variations in water clarity, residual sunglint, and suspended sediments can reduce contrast between benthic features. Even after sunglint correction, some surface reflection can persist, especially in areas with active wave motion **(Hedley *et al.*, 2012)**. These factors can increase spectral noise and reduce the separability of closely related classes.

6. Implications for high-resolution mapping

Despite these limitations, the accuracy metrics indicate strong agreement between the classified habitats and field data. An overall accuracy above commonly accepted thresholds for shallow-water mapping demonstrates that Planet Scope imagery is appropriate for detailed benthic assessment around small islands. The Kappa coefficient indicates substantial agreement, supporting the reliability of the classification.

The spatial patterns revealed in the habitat map provide a useful baseline for monitoring ecological change around Tikus Island. Areas with extensive live coral may serve as indicators of reef health, while rubble-dominated regions may signify past disturbance or areas needing closer management attention. The presence of macroalgae in specific zones suggests potential environmental gradients that merit further study. Together, these patterns highlight the importance of high-resolution imagery for capturing habitat complexity and informing management strategies.

CONCLUSION

This study produced a high-resolution benthic habitat map for the shallow waters of Tikus Island using Planet Scope imagery supported by field observations. The classification identified six major habitat types and achieved accuracy values that indicate strong agreement between satellite-derived outputs and ground-truth data. The resulting map provides a detailed baseline of benthic conditions, capturing spatial patterns that were not observable in earlier medium-resolution assessments.

These findings offer practical value for monitoring reef condition and guiding coastal resource management in Bengkulu Province. The high-resolution map can assist in identifying areas that require protection, restoration, or continued observation, particularly in zones where live coral and rubble are concentrated.

Future research may benefit from applying time-series Planet Scope imagery or integrating machine-learning classification methods to improve detection of habitat changes and to enhance long-term monitoring capacity. These habitat patterns are directly relevant for spatial planning and conservation. The map can support zoning decisions by identifying areas of high coral cover, guide routine monitoring by highlighting zones susceptible to degradation, and assist managers in prioritizing sections of the reef for restoration or community-based stewardship.

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