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RESEARCH ARTICLE

Analysis of Mangrove Health Index (MHI) for Mapping Mangrove Forest Health Based on Sentinel 2A Satellite Imagery in Ecotourism Kampung Blekok, Situbondo

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ABSTRACT

Ecotourism Kampung Blekok, located in Situbondo Regency, is a conservation-focused mangrove forest area in Indonesia. Mangrove ecosystems are highly sensitive to threats posed by anthropogenic activities and natural disturbances, necessitating regular monitoring. This study employed remote sensing technology combined with direct field observations to assess the health status of mangrove forests. The Mangrove Health Index (MHI) method was utilized, incorporating the Google Earth platform and the MonMang 2.0 application for analysis. Sentinel-2A satellite imagery was analyzed using vegetation indices such as the Normalized Burn Ratio (NBR), Green Chlorophyll Index (GCI), Structure-Insensitive Pigment Index (SIPI), and Atmospherically Resistant Vegetation Index (ARVI). Field-based MHI calculations considered three key parameters: canopy cover percentage, mean stem diameter, and sapling density. The multitemporal analysis of MHI revealed a reduction in the area of mangroves classified as poor health in 2021, which subsequently increased by 2023, while mangroves in the moderate health category expanded consistently from 2019 to 2023. Notably, the expansion of mangrove areas in moderate and excellent health categories suggests ecosystem improvement driven by rehabilitation efforts and natural recovery processes. An accuracy assessment of the imagery classification yielded an overall accuracy of 93.33% and a kappa coefficient of 84.73%, indicating high reliability and precision in the classification results.

INTRODUCTION

Mangroves are dicotyledonous plants that thrive in intertidal zones, including coastal shores, river estuaries, and lagoons, particularly in tropical regions with flat and wave-protected coastlines (Kristianto et al., 2021). These ecosystems play a vital role in coastal stability through their robust root systems, which act as barriers against abrasion, sediment traps, and wave dampeners, forming a complex and dynamic ecological system (Farhaby et al., 2020). Despite these ecological benefits, public awareness of the importance of mangrove forests remains limited, contributing to significant degradation. In Indonesia, approximately 5.9 million hectares of mangroves have been destroyed out of a total 8.6 million hectares, mainly due to anthropogenic activities (Al Muhdar et al., 2021).

Degradation of mangrove forests is also prevalent in Situbondo Regency, primarily due to land-use changes, such as conversion to settlements, aquaculture, roads, and industrial zones, which have significantly reduced mangrove coverage (Suryaningsih and Hudha, 2018). Situbondo Regency, a coastal region on Java Island, harbors approximately 725.02 hectares of mangrove forests (Dinas Lingkungan Hidup Kab. Situbondo, 2017). Among these, Kampung Blekok serves as a prominent conservation-based ecotourism area, encompassing about 18 hectares of mangrove forest. This area highlights the need for ongoing conservation efforts to preserve and restore mangrove ecosystems.

Monitoring mangrove forest health is critical for evaluating their ecological condition and mitigating further degradation (Safe'i et al., 2019). One effective approach for such monitoring is the application of multitemporal analysis through remote sensing technology. Remote sensing allows for the observation of ecosystems without direct physical contact by utilizing satellite imagery, offering a modern and efficient method for ecosystem assessment (Hardiana, 2023). Among various satellite platforms, Sentinel-2A, with its 10-meter spatial resolution, provides high-quality imagery suitable for assessing mangrove health with considerable accuracy (Tavora et al., 2023).

The Mangrove Health Index (MHI) is a widely recognized method for evaluating mangrove forest health. This index incorporates parameters such as canopy cover, stem diameter, and sapling density to determine the overall condition of mangrove ecosystems. MHI values can be derived through field data collection or estimated using remote sensing data, such as Sentinel-2A imagery (Schaduw et al., 2021). The assessment of mangrove health through satellite data involves vegetation indices, including the Normalized Burn Ratio (NBR), Green Chlorophyll Index (GCI), Structure-Insensitive Pigment Index (SIPI), and Atmospherically Resistant Vegetation Index (ARVI) (Hidayah et al., 2023).

Additionally, the study explores the relationship between satellite-derived MHI values and canopy cover by conducting accuracy tests for image classification. Remote sensing-based monitoring offers an innovative approach to modeling mangrove health using the MHI index, providing a detailed overview of mangrove forest conditions. This approach is applied in Ecotourism Kampung Blekok to assess and support conservation and management strategies for sustaining mangrove ecosystems.

METHODOLOGY

The research was conducted at the Kampung Blekok Mangrove Ecotourism area in Situbondo Regency in February 2024. This study utilized a survey method with an associative approach, a quantitative technique designed to collect data for analyzing past and present conditions. Sampling was carried out using a purposive sampling method based on mangrove health categories identified through transect sampling. Each transect covered an area of 100 m^2, with a plot size of 10 x 10 meters, aligning with the spatial resolution of Sentinel-2A satellite imagery, which features a 10-meter resolution.

The transects were strategically placed to represent varying mangrove cover density categories, including sparse, moderate, and dense, ensuring comprehensive data collection across the full spectrum of mangrove health conditions. Each observation point was marked by a single transect, resulting in a total of 12 observation points. These points were selected to correspond to mangrove density classes observed directly in the field, providing a robust dataset for the analysisof mangrove health.

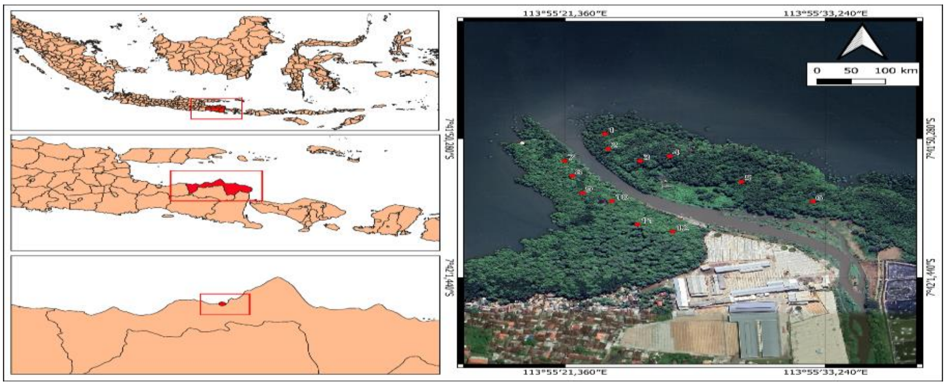

Figure 1: Research location

Data analysis

The Sentinel 2A satellite imagery was processed using Google Earth Engine (GEE), utilizing specific spectral bands: Band 2 (Blue), Band 4 (Red), Band 8 (Near Infrared), Band 3 (Green), and Band 11 (Shortwave Infrared). The processed imagery was exported for layout design in QGIS 3.3.0.

Vegetation indices supporting the MHI formula, such as NBR, GCI, SIPI, and ARVI, were calculated as follows:

NBR (Normalized Burn Ratio)

$$NBR = \frac{(NIR - SWIR)}{(NIR + SWIR)}$$

GCI (Green Chlorophyll Index):

$$GCI = \left(\frac{NIR}{green}\right) - 1$$

SIPI (Structure Insensitive Pigment Index):

$$SIPI = \frac{(NIR - blue)}{(NIR + red)}$$

ARVI (Atmospherically Resistant Vegetation Index):

$$RVI = \frac{(NIR - 2.red + blue)}{(NIR + 2.red + blue)}$$

The Mangrove Health Index (MHI) analysis aims to determine the health of mangrove forests in the study area. This process begins with identifying and calculating species density (Di) and relative density (RDi) of mangrove vegetation. The MHI analysis in this study was supported by the MonMang 2.0 application. According to Syari et al. (2021), MonMang 2.0 applies the following formula to calculate MHI:

Where **MHI** is Mangrove Health Index (%); **Sc** is Canopy Coverage Score (%); **Sd** is Diameter at Breast Height Score (cm); **Snsp** is Sapling Count per Area Score

MHI analysis is based on three key parameters: canopy cover percentage (Sc), average tree diameter (Sd), and sapling density per plot (Snsp). The MHI values are categorized into three classes:

Table 1: MHI value classification

Category	Percentage
Poor	< 33.33%
Moderate	33.33% – 66.67%
Excellent	> 66.67%

Accuracy testing

Accuracy testing was carried out to evaluate the correspondence between satellite imagery representations and actual field conditions, based on object characteristics and observed landform changes. Ground verification was conducted at 30 randomly distributed points, and the results were analyzed using a confusion matrix. The producer's and user's accuracy values were averaged to calculate the kappa coefficient, which serves as a measure of the map's reliability and overall classification accuracy.

Table 2: Kappa class interpretation

Kappa Value	Reliability Level
< 0,2	Very Low
0,2 – 0,4	Low
0,4 – 0,6	Moderate
0,6 – 0,8	Strong
0,8 – 1,0	Very Strong

RESULTS

Area of the research location

The coastal ecosystem of Situbondo Regency (East Java Province, Indonesia) encompasses a significant mangrove conservation zone situated in Klatakan Village, Kendit Subdistrict (7°42'S, 113°56'E). A notable component of this ecosystem is the Blekok Ecotourism Site, established 10 kilometers from the urban center of Situbondo. This protected area serves as a critical habitat for Ardeidae species (herons) and contains a diverse assemblage of mangrove vegetation, primarily dominated by Avicennia marina and Rhizophora mucronata. The site received formal conservation status through Regional Legislative Decree No. 13/2017, establishing it as a designated ecotourism zone. Site management is implemented through a collaborative governance framework involving a Community-Based Tourism Management Group (POKDARWIS) in conjunction with the Municipal Environmental Agency and private sector stakeholder PT. Paiton Energy Probolinggo. The conservation area's infrastructure includes elevated walkways traversing the mangrove forest, facilitating both recreational access and scientific observation of the ecosystem. This area as shown in **Figure 2.**

Figure 2: Kampung Blekok Ecotourism Location: a. mangrove forest; b jogging track

Mangrove health index (MHI) analysis based on satellite imagery

The mangrove health maps using the MHI index for Kampung Blekok Ecotourism for the years 2019, 2021, and 2023 are presented in **Figure 3**. Comparisons of MHI values and trends in mangrove area changes by MHI category are shown in **Figures 4** and **5**.

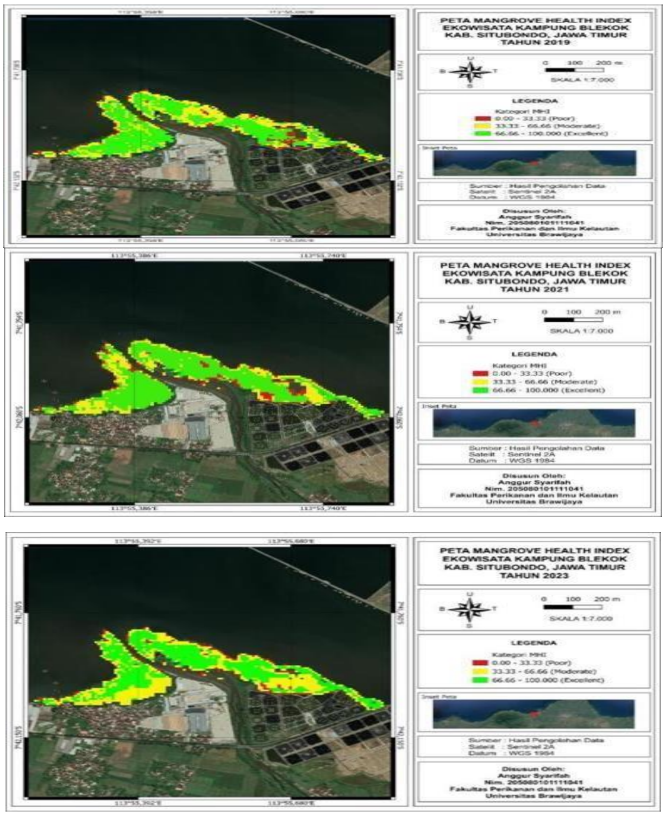

Figure 3: MHI Calculation Results for Kampung Blekok Ecotourism using the GEE Platform: (a). 2019 Map; (b). 2021 Map; (c). 2023 Map

The MHI values in 2019 ranged from 30.01% to 66.85%, increasing to 28.91%–67.29% in 2021, but decreasing to 20.46%–56.25% in 2023. The mangrove area under the MHI health categories expanded from 11.824 ha in 2019 to 11.903 ha in 2021, and to 14.030 ha in 2023. Most mangroves were categorized as "moderate," reflecting ecosystem improvement despite a decline in MHI in 2023. Environmental factors influencing mangrove regeneration include exposure to tides at the forest's edge, plastic waste, and barnacle infestations observed on mangrove trunks, particularly in the sapling and standing categories. Strong tidal currents also hinder the growth of seedlings and saplings with weak roots. However, the continuous increase in mangrove area is attributed to conservation efforts through rehabilitation, increased community awareness of the ecosystem's importance, and natural recovery processes. The expansion of mangrove areas in the moderate to excellent health categories signifies ecosystem sustainability in the region.

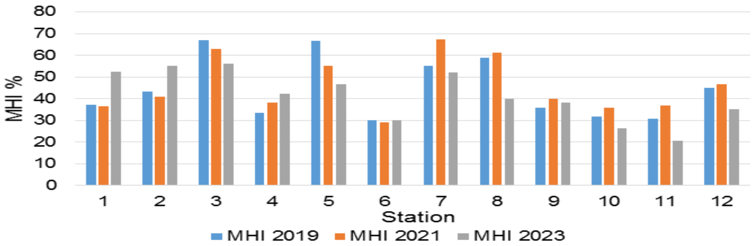

Figure 4: Comparison of MHI values from 2019, 2021, and 2023

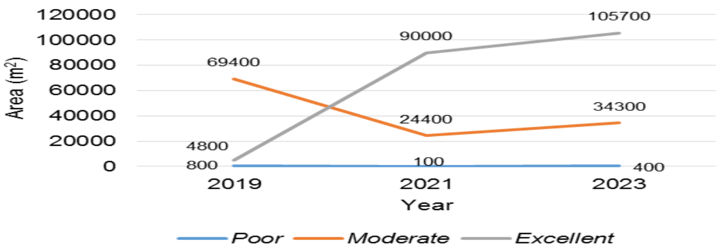

Figure 5: Trends in mangrove area changes by MHI categories from 2019 to 2023

Mangrove health index (MHI) analysis based on field observations

Field-based MHI classifications were conducted using the MonMang 2.0 application, involving several stages and data analyses to determine the health of mangrove forests in the study area. The field data collection process included creating transects, determining coordinates, measuring canopy cover using the hemispheric photo method, measuring trunk circumference at breast height (CBH), and determining sapling density per area.

Canopy coverage score (Sc)

Canopy cover percentages ranged from 25.4% to 72.2% across Stations 1 to 12, with an average of 61.58%. Stations 3 and 4 had the highest canopy coverage (72.2%), while Station 6 had the lowest (25.4%). The canopy coverage score (Sc) ranged from 0 to 5%, with the highest value at Station 2 (4.9) and the lowest at Stations 6 and 10. The mangrove canopy cover percentage in Kampung Blekok Ecotourism varies depending on mangrove species and substrate conditions. Conservation areas have an average canopy cover of 62.35%, classified as moderate according to the Keputusan Menteri Lingkungan Hidup No. 201 Tahun 2004. Meanwhile, ecotourism areas exhibit an average canopy cover of 61.6%, falling within the moderate to sparse category.

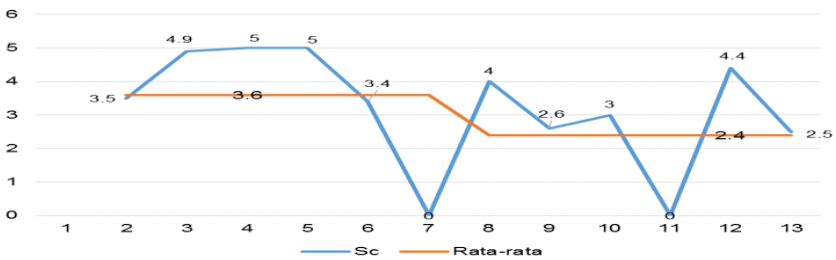

Figure 6: Canopy coverage score graph (Sc)

Diameter at breast height score (Sd)

The average DBH values of mangrove trunks ranged from 10.1 cm to 20 cm across all stations, with an overall average of 12.8 cm. Station 4 recorded the highest average DBH (10.4), while Station 10 had the lowest (5.9) (Figure 7).

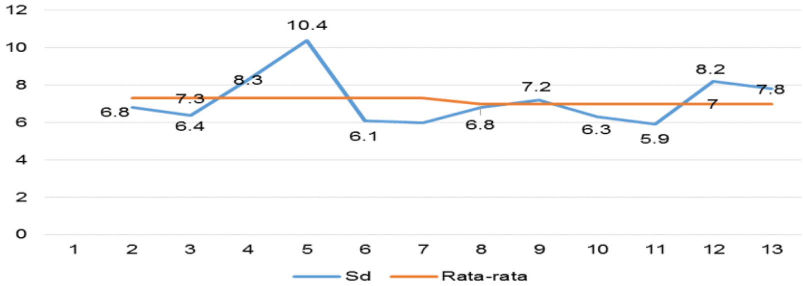

Figure 7: **Diameter at breast height score graph (Sd)**

Sapling density score (Snsp)

Sapling densities ranged from 3 to 20 individuals per area, with Station 7 having the highest density (20 individuals) and Station 6 the lowest (3 individuals). The highest sapling density score (Snsp) was observed at Station 7 (6.7), while the lowest was at Station 6 (4.5) (Figure 8). The average sapling density across all stations was approximately 10 individuals per unit area. Stations 7 to 9 exhibited higher sapling densities, primarily dominated by Avicennia marina and Rhizophora stylosa. In contrast, other stations had lower sapling densities due to the prevalence of large mangrove trees, which limited available open space for sapling establishment and growth. The presence of large-diameter mangrove stands increases competition for space, thereby restricting the growth of seedlings and saplings (Dewi et al., 2021). Mangrove regeneration occurs as saplings develop into mature trees, contributing to the sustainability of the ecosystem (Heriyanto & Subiandono, 2016).

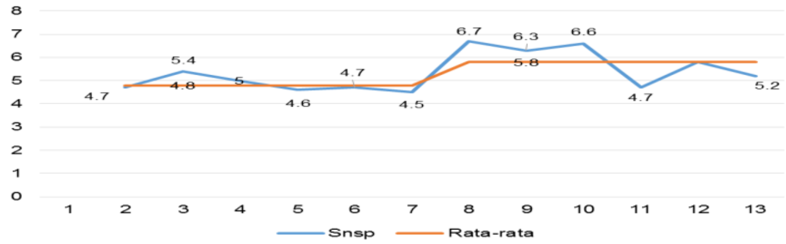

Figure 8: Sapling density score graph (Snsp)

Pantai Indah Kapuk and Pantai Marunda have a flat slope (0-8%) with a dominant green color on the map, while Pantai Ancol has a gently sloping beach (8-15%) with a dominant yellow color. The slope levels of these beaches can indicate the vulnerability of the coastal areas to abrasion, flooding, and coastline changes (Hamuna et al., 2018).

Overall field-based MHI analysis

MHI values ranged from 44.7% to 63.6% across Stations 1 to 12, with an average of 53.5%. The conservation area's average MHI was 53.7%, while the ecotourism area's average was 53.3% (**Figure 10**). MHI map of Blekok Village Ecotourism can be seen in (**Figure 9)**

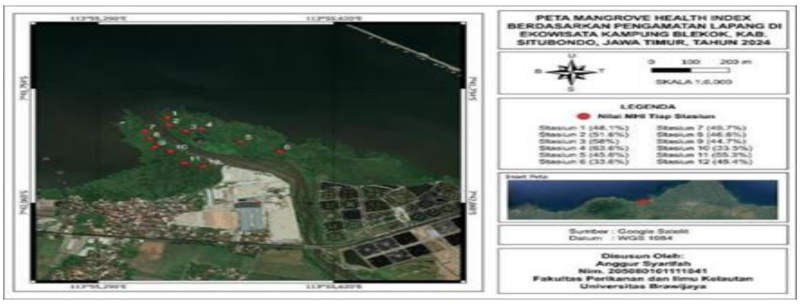

Figure 9: Kampung Blekok MHI Map for 2024

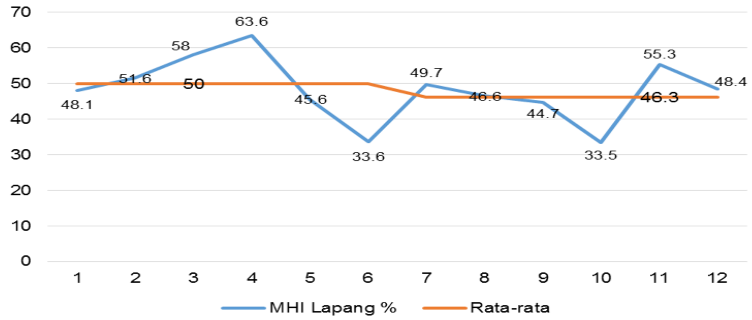

Figure 10: Field-based MHI data analysis

Tree distribution analysis

The total area of the study site is 19.167 ha, with the conservation area on the eastern side covering 11.467 ha and the ecotourism area on the western side covering 7.7 ha (**Table 3**). The total number of mangrove trees across 12 stations was 31,147.

Table 3: Mangrove area across stations

Station	Area (ha)
1	0,446
2	0,722
3	1,091
4	0,908
5, 6	8,300
7	0,752
8	0,623
9	0,424
10	0,635
11,12	5,266
Total	19,167

Mangrove species distribution

According to biodiversity records, the Kampung Blekok Ecotourism area contains 16 mangrove species. Frequently encountered species include *Sonneratia alba*, *Rhizophora mucronata*, *Avicennia marina*, and others, with *Avicennia marina* being the most dominant.

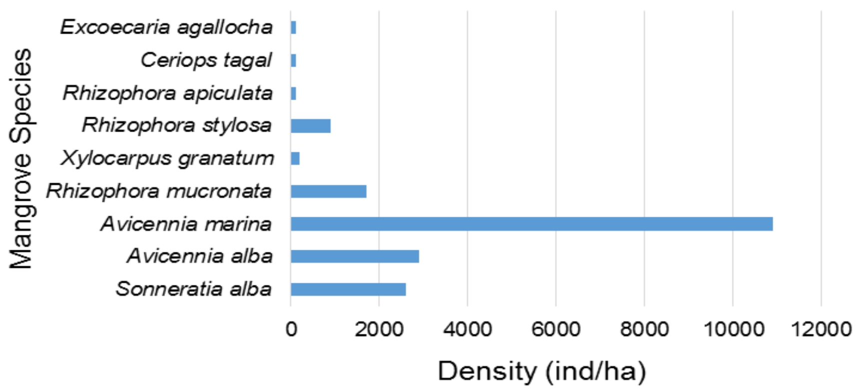

Figure 11: Species density in Kampung Blekok Mangroves

Accuracy test for satellite data

Accuracy testing of MHI canopy cover was performed on 30 sample points, achieving an overall accuracy of 93.33% and a kappa accuracy of 84.73%, indicating a reliable classification suitable for further analysis (**Figure 12**).

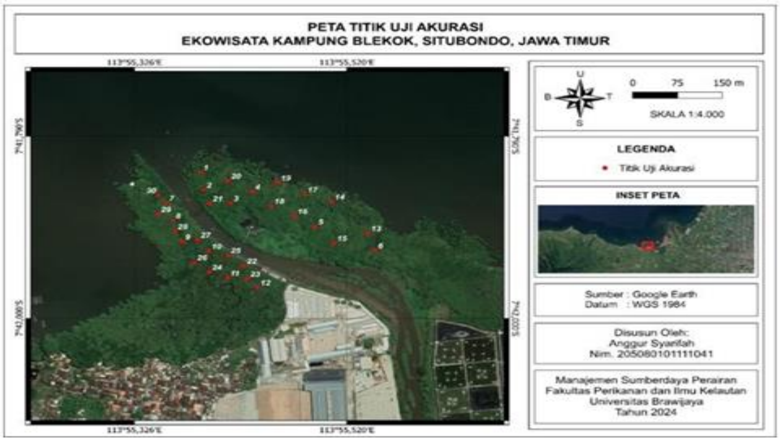

Figure 12: Accuracy test sampling locations

The confusion matrix calculation is based on the overall ground check results between field data and MHI index images. The confusion matrix results for the vegetation index are presented in **Table 4**, and the comparison of producer and user accuracy tests are presented in **Table 5** and **Table 6.**

Table 4: Confusion matrix accuracy test

Image / Field	Rare	Medium	Heavy	Total Correct	Total
Rare	6	0	1		7
Medium	0	21	1		22
Heavy	0	0	1		1
Total Correct				28	
Total	6	21	3		30

Table 5: **Producer accuracy test**

Field	*Producer's Accuracy*	% accuracy
Rare	6/6	100
Medium	21/21	100
Heavy	1/3	33,33
	Average	77,77

Table 6: User accuracy test

Field	*User's Accuracy*	% accuracy
Rare	6/7	85,71
Medium	21/22	95,45
Heavy	1/1	100
	Average	77,77

The results of the accuracy test calculation show that the overall accuracy value reaches 93.33%. The average producer's accuracy value was recorded at 77.77%, with an omission error of 22.23%. Meanwhile, the average user's accuracy reached 93.72%, with a commission error rate of 6.28%.

CONCLUSION

The results of Mangrove Health Index (MHI) analysis using Sentinel 2A satellite imagery show significant dynamics in mangrove health conditions from 2019 to 2023. Despite fluctuations in MHI values, mangrove forest area increased from 11,824 ha in 2019 to 14,030 ha in 2023, with an increase in the moderate and excellent health categories. This improvement was supported by rehabilitation and natural recovery processes, although anthropogenic pressures such as garbage and industrial waste pollution, as well as barnacle infestation and tidal flooding caused some areas to be in the poor category. Image classification accuracy reached 93.33% with a kappa value of 84.73%, indicating the results of this analysis have a good level of image classification accuracy.

This research emphasizes the importance of management and rehabilitation to support the sustainability of mangrove ecosystems.

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AUTHOR CONTRIBUTIONS

UZ was responsible for Funding Acquisition, Formal analysis, Supervision, and Validation. ANR was responsible for Conceptualization, Data curation, Formal analysis, and Writing original draft; AS were responsible for Investigation, Methodology, Resources, and Software; and All authors were responsible for Writing – review and editing.

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