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Spatial-temporal analysis of Sunda Strait Mangrove Health Index (MHI) via Sentinel-2 for sustainable blue economy

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Abstract. Continuous monitoring of mangrove forest conditions is essential to support a sustainable blue economy through informed land use planning, conservation, and rehabilitation strategies. This study investigates the spatial and temporal dynamics of the Mangrove Health Index (MHI) in the Sunda Strait region using Sentinel-2 satellite imagery for the years 2015, 2020, and 2025, focusing on the Sumur Coastal Area, Pandeglang, Banten. The analysis utilized three vegetation indices: the Normalized Burn Ratio (NBR), Green Chlorophyll Index (GCI), and Structure-Insensitive Pigment Index (SIPI). Results indicate a positive trend in ecosystem health. The average NBR increased from 0.416 in 2015 to 0.450 in 2025, GCI from 1.14 to 4.88, and SIPI from 0.84 to 1.04. Mangrove areas in poor condition (MHI < 33.3%) decreased from 684.15 ha to 376.78 ha, while areas in very good condition (MHI > 66.8%) increased from 548.39 ha to 945.29 ha. The moderate condition category (33.3% ≤ MHI ≤ 66.8%) declined from 3,124.11 ha to 2,159.87 ha. These findings highlight significant mangrove vegetation recovery, though some degradation persists due to land conversion. This research provides a scientific contribution to the development of a remote sensing-based mangrove health monitoring method with the integration of multitemporal vegetation indices and field survey validation. This approach can be replicated in other coastal areas as a basis for decision-making in sustainable mangrove ecosystem management.

Keywords: Mangrove Health Index, Banten, Normalized Burn Ratio, Green Chlorophyll Index, Remote Sensing

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1 Introduction

The mangrove ecosystem in the coastal area of the Sunda Strait, including the Sumur region of Pandeglang, Banten, plays a vital role in maintaining the ecological balance and supporting the sustainability of the blue economy [1]. Mangroves serve as natural coastal protectors against erosion, efficient carbon sinks, and habitats for a wide range of flora and fauna [2]. Additionally, mangroves act as natural barriers against dangerous ocean waves, reducing the impact of natural disasters, such as tsunamis and tropical storms [3]. They also support the livelihoods of coastal communities by providing natural resources such as food, building materials, and fuel. However, pressures from land conversion, coastal development, and pollution have caused degradation at various locations, including the Sunda Strait coast [4]. Furthermore, the impacts of climate change, such as rising sea surface temperatures, sea-level rise, and changes in rainfall patterns, have worsened mangrove conditions and threatened their sustainability. Various anthropogenic pressures, such as land conversion, pollution, and coastal development, combined with the impacts of global climate change, have led to the widespread degradation of mangrove ecosystems in many regions [5]. The loss of mangroves could potentially increase coastal damage, reduce biodiversity, and exacerbate the impacts of climate change [6].

Therefore, monitoring the health of mangroves is crucial. Accurate monitoring can provide valuable data to support conservation policies and sustainable natural-resource management [7]. Remote sensing using satellite data is one of the technologies that can be used to monitor mangrove health. Sentinel-2, as part of the Copernicus program managed by the European Space Agency (ESA), provides high-resolution imagery with wide coverage. These data enable large-scale monitoring of mangroves in both spatial and temporal dimensions [8-10]. The use of Sentinel-2 imagery allows for more efficient and timely monitoring of mangrove ecosystems, offering a more comprehensive picture of ecosystem conditions within a shorter timeframe [11].

The Mangrove Health Index (MHI) is used to assess the health of mangrove ecosystems. The MHI combines various ecological parameters that reflect mangrove health such as canopy cover, vegetation density, and ecosystem structure. The Mangrove Health Index (MHI) was introduced as a quantitative approach based on vegetation parameters [12]. By integrating vegetation indices derived from satellite imagery, mangrove health can be mapped spatially and temporally at a more cost-efficient scale compared to full field surveys. Vegetation indices derived from satellite imagery have been shown to provide accurate representations of ecosystem conditions, including stand density, canopy cover, and chlorophyll content [13, 14]. Using Sentinel-2 imagery, the MHI can be calculated to identify temporal changes. This provides clear insights into mangrove health status, which is critical for supporting ecosystem-based management and more targeted conservation strategies [15].

The coastal area of Sumur in the Pandeglang Regency, Banten, serves as an entry point to the Sunda Strait and is located near Ujung Kulon National Park. The mangrove ecosystem in this region plays a vital role as a wave buffer and supports local capture fisheries but is under pressure from land conversion into aquaculture ponds and settlements [26]. Therefore, a comprehensive study over the past decade is needed to evaluate the dynamics of mangrove health. This study aimed to analyze the spatial and temporal dynamics of mangrove vegetation indices: Normalized Difference Vegetation Index (NDVI), Normalized Burn Ratio) NBR (Green Chlorophyll Index); GCI), Structure Insensitive Pigment Index (SIPI), and Atmospherically Resistant Vegetation Index (ARVI) in the Sumur coastal area for the years 2015-2025 and mapping changes in MHI classes as a basis for conservation and rehabilitation planning of mangrove ecosystems using data-driven approaches. The results of this study are expected to provide deeper insights into the health of mangrove ecosystems in the Sunda Strait. This study addresses the information gap related to the lack of quantitative studies integrating the multitemporal spatial analysis of Sentinel-2 imagery with field data to assess mangrove health dynamics in tropical coastal areas. Most previous studies have focused on mapping mangrove distribution without linking it to the systematically measured health indices. Therefore, the Mangrove Health Index (MHI) approach developed in this study provides a new methodological foundation for assessing mangrove ecosystem conditions more comprehensively and can be replicated in other coastal areas. The information obtained will be useful for designing more sustainable, evidence-based coastal resource management policies.

2 Research methodology

This research methodology adopted a systematic approach to conduct spatio-temporal analysis of the Mangrove Health Index (MHI) using Sentinel-2 satellite imagery. The methodology consisted of several steps, including data collection, image processing, analysis, and interpretation of the results, all of which were designed to achieve the research objectives. A more detailed explanation of each study stage is presented in **Fig. 1**.

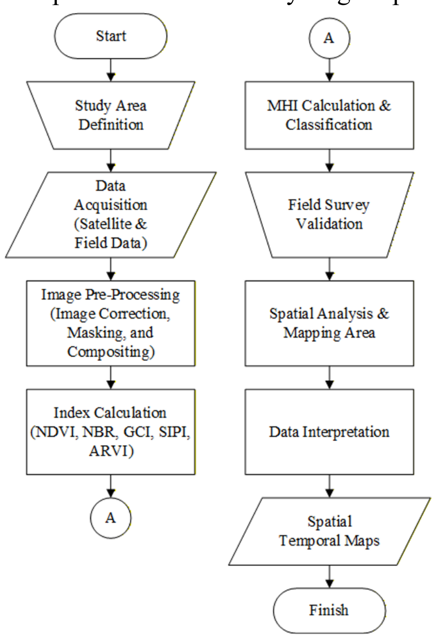

Fig. 1. Research flowchart.

2.1 Study area

The study area covered mangrove ecosystems located along the coast of Sumur District in Sunda Strait. This area was selected because it hosts relatively large and diverse mangrove ecosystems that play vital roles in coastal protection and biodiversity sustainability in the region. The geographical location of these sites provides an important context for monitoring mangrove ecosystems, which are also influenced by local environmental dynamics and climate change.

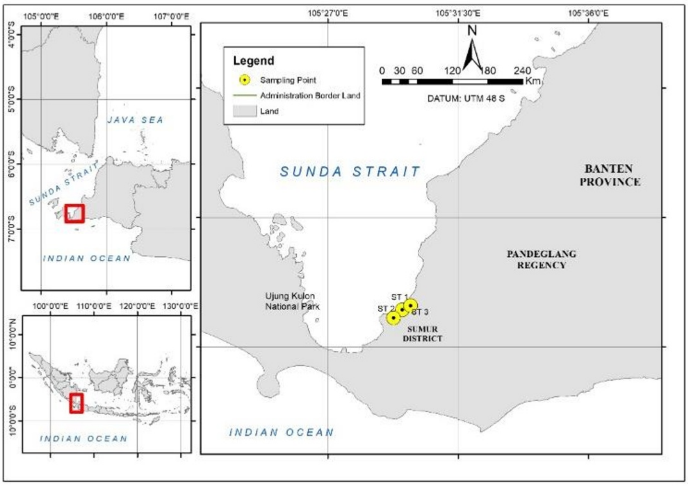

Fig. 2. Study area.

Sampling was conducted in mangrove ecosystems in the Cikawung area, indicated by yellow dots. Sampling was conducted to ground-check and identify the structure of the mangrove community.

2.2 Data collection

The data for this study were obtained from Sentinel-2 satellite imagery provided by the Copernicus program and managed by the European Space Agency (ESA). Sentinel-2 was chosen for its high spatial resolution (10 m in selected bands) and wide coverage, enabling a detailed representation of mangrove ecosystems along coastal areas. The datasets included Level-1C and Level-2A imagery accessed through the Copernicus Open Access Hub (https://colhub.copernicus.eu). The temporal coverage spans 2015–2025, with annual acquisitions designed to monitor mangrove ecosystem changes including degradation and rehabilitation patterns. Multitemporal data are essential because mangrove ecosystems are highly dynamic and are influenced by tidal fluctuations, sedimentation, and anthropogenic activities.

2.3 Field survey

Field data were collected using the quadrat transect method, which is commonly applied in mangrove studies. Three stations were set with three plots measuring 10 × 10 m, plotted perpendicular to the shoreline, due to the differentiation of mangrove species composition. Plot spacing ranged from 10 m to 15 m, and locations were chosen for vegetation representativeness and accessibility. In each plot, species were identified, individuals were counted, DBH was measured, and canopy cover was estimated. These data were used to calculate the Importance Value Index (IVI) derived from the relative density, frequency, and cover, with values ranging from 0 to 300. Higher IVI values indicate greater ecological dominance of the species [27]. Environmental conditions such as substrate type, litter, and anthropogenic activities were also recorded. Field observations validated satellite interpretation and supported Mangrove Health Index (MHI) analysis, allowing a more comprehensive assessment of mangrove conditions across community structures and spatio-temporal dynamics.

2.4 Data processing

Sentinel-2 imagery must be preprocessed to ensure data quality and accuracy. The first step is atmospheric correction using the Sen2Cor algorithm in the Sentinel Application Platform (SNAP) to reduce influences such as aerosols and water vapor, thereby producing more accurate surface reflectance. The next step is georeferencing, aligning imagery to the Universal Transverse Mercator (UTM) projection with the WGS 84 datum to maintain spatial consistency. Cloud screening was then performed using the Fmask algorithm to remove pixels affected by clouds and shadows, leaving only valid land cover. Mosaicking is the final step, which combines multiple images acquired at different times into a complete dataset that covers the study area. This process is important because mangroves are unevenly distributed along the coastal zones. The resulting imagery provided a comprehensive spatial representation of ecosystem conditions and was ready for vegetation index analysis, forming the basis for calculating the Mangrove Health Index (MHI).

2.5 Data analysis

The data analysis in this study used Sentinel-2 imagery that had undergone preprocessing steps such as atmospheric correction, georeferencing, cloud masking, and mosaicking. The processed data were then used to generate vegetation indices as the basis for calculating the Mangrove Health Index (MHI). The indices applied were NDVI, NBR, GCI, SIPI, and ARVI, each chosen for their sensitivity to key mangrove parameters, such as stand density, canopy cover, chlorophyll content, and vegetation physiology. NDVI effectively describes mangrove canopy density and health [28, 29]. NBR detects degradation or vegetation stress. GCI provides chlorophyll information linked to photosynthesis, SIPI reflects pigment balance and physiological stability, and ARVI reduces atmospheric disturbances, which are useful in humid coastal areas. Together, these indices offer a comprehensive view of mangrove conditions. The vegetation index formula and the MHI calculation utilizing Sentinel-2B satellite imagery are shown in the following equations [30]:

$$\text{NDVI} = \frac{(\text{NIR-RED})}{(\text{NIR+RED})} \tag{1}$$

$$\text{NBR} = \frac{(\text{NIR - SWIR})}{(\text{NIR+ SWIR})} \tag{2}$$

$$\text{GCI} = \frac{(\text{NIR})}{(\text{GREEN-1})} \tag{3}$$

$$\text{SIPI} = \frac{(\text{NIR - BLUE})}{(\text{NIR-RED})} \tag{4}$$

$$\text{ARVI} = \frac{(\text{NIR - 2RED + BLUE})}{(\text{NIR+ 2RED + BLUE})} \tag{5}$$

$$\text{MHI} = 102{,}12\ \text{NBR} - 4{,}64\ \text{GCI} + 178{,}15\ \text{SIPI} \tag{6}$$

where:
NIR, near-infrared band (B8); Green = Green Band (B4); SWIR, short-wave infrared band (B11); Blue = Blue Band (B2); Red = Red Band (B4)

The integration of these indices generates MHI values that represent the spatial and temporal health of the mangrove ecosystems. MHI classification is divided into poor (MHI < 33.3%), moderate (33.4–66.7%), and good (MHI > 66.8%) [30, 31]. This index consists of several categories that classify the level of mangrove health.

- Excellent: Mangroves are in a healthy condition, characterized by extensive canopy cover and high vegetation density. Ecosystems have a strong capacity to provide ecological services, including coastal protection, carbon storage, and biodiversity support.
- Moderate: Mangrove conditions show signs of decline with minor degradation or external pressures such as pollution or land conversion. Canopy cover and vegetation density are reduced, which may affect the ecosystem's ability to provide optimal ecological services.
- Poor: Mangroves are in poor condition with a significant decline in canopy cover and vegetation density. Vegetation loss occurs because of land conversion, pollution, or other factors that diminish the ecosystem's capacity to provide ecological services and coastal protection. This condition requires serious attention during restoration [12, 18, 32].

3 Results and discussion

This chapter presents the results of the spatiotemporal analysis of mangrove ecosystems in the Sumur coastal area using Sentinel-2 imagery and field surveys. The findings are organized to explain mangrove cover dynamics, Mangrove Health Index (MHI) classification, vegetation indices, community structure, influencing factors, and their implications for conservation and rehabilitation. Each subsection combines quantitative and qualitative aspects to provide a comprehensive understanding of the mangrove conditions and trends in the study area.

3.1 Dynamics of mangrove forest area

Satellite image analysis revealed a significant increase in mangrove forest cover in the Sumur coastal area between 2015 and 2025. In 2015, mangroves covered about 3,500 ha, expanding to more than 4,000 ha by 2025, showing a positive trend in mangrove expansion. This growth has been linked to successful rehabilitation programs by the government and local communities since 2019 (after the tsunami 2018) [33, 34], particularly the Ujung Kulon National Park authority, and stricter coastal spatial planning regulations. Sedimentation in river estuaries also provides new substrates for mangrove growth, especially for pioneer species, such as *Avicennia marina* and *Rhizophora mucronata*. Ecologically, this expansion strengthens shoreline protection, habitat provision, and blue carbon sequestration. The observed increase in mangrove cover between 2015 and 2025 can be seen as both an indicator of successful coastal ecosystem management and a key asset for resilience to climate change.

This figure shows the distribution and extent of mangrove forests in 2015, 2020, and 2025, derived from multitemporal Sentinel-2 imagery. The maps indicate a clear increase in mangrove coverage over the ten-year period, particularly along the coastal areas of Sumur District and adjacent to Ujung Kulon National Park, suggesting successful natural regeneration and rehabilitation efforts, as well as the influence of coastal sedimentation processes on mangrove expansion.

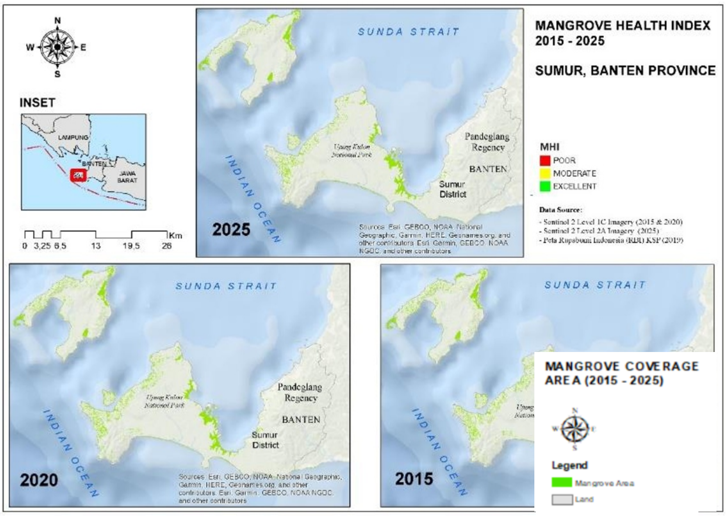

Fig. 3. Spatial-temporal changes in mangrove cover in the Sunda Strait Region (2015, 2020, and 2025).

3.2 Mangrove Health Index (MHI) classification

The analysis of Mangrove Health Index (MHI) values indicated a significant improvement in the health of mangrove ecosystems within the study area. In 2015 and 2020, most mangrove areas were classified as moderate (33.4% < MHI < 66.7), reflecting limited vegetation health and ecosystem instability. In 2025, however, a substantial increase was observed in areas categorized as good (MHI > 66.8%), particularly within Ujung Kulon National Park, signifying clear signs of ecosystem recovery (Maulani et al., 2021). Mangrove areas in poor condition decreased from 684.15 ha to 376.78 ha, while areas in very good condition increased from 548.39 ha to 945.29 ha. The moderate category (33.3% ≤ MHI ≤ 66.8%) declined from 3,124.11 ha to 2,159.87 ha. These findings highlight notable mangrove vegetation recovery, although some degradation persists because of land conversion.

This change reflects the positive impact of rehabilitation measures, including mangrove replanting, coastal protection, and regulation of anthropogenic activities. The decline in moderately healthy areas indicates that much of the vegetation has improved in quality, as demonstrated by the higher stand density, greater canopy cover, and increased chlorophyll content. Nevertheless, the persistence of areas with moderate-to-poor MHI values shows that challenges remain in sustaining ecosystem health, especially in locations exposed to logging, land conversion, excessive sedimentation, or pollution. From an ecological perspective, the improvement in mangrove conditions reflected by higher MHI values has important implications. Healthier mangrove ecosystems can deliver ecosystem services more effectively, including providing habitats for diverse species, serving as natural wave buffers, and acting as blue carbon sinks. The positive trend of increasing mangrove areas classified as good in 2025 not only demonstrates the success of rehabilitation programs, but also strengthens the role of mangroves as natural barriers against the threats of climate change and coastal degradation.

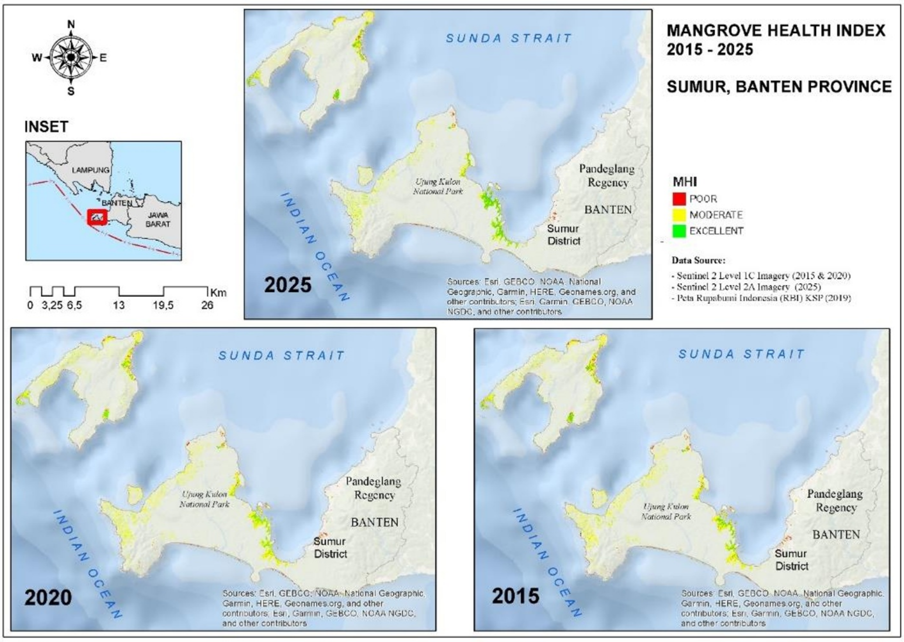

Fig. 4. Spatial-temporal analysis of Mangrove Health Index (MHI) in Sumur, Banten Province from 2015 to 2025.

The upper panels illustrate changes in mangrove coverage for 2015, 2020, and 2025, derived from multitemporal Sentinel-2 imagery, highlighting the overall expansion of mangrove areas along the Sumur coast and around Ujung Kulon National Park. The lower panels present the Mangrove Health Index (MHI) classification for the same years, showing a transition from predominantly moderate and poor conditions in 2015 toward improved and healthier mangrove conditions by 2025, reflecting the combined effects of natural regeneration, sedimentation processes, and rehabilitation efforts.

3.3 Vegetation index

The analysis of vegetation indices in the mangrove ecosystem at the study site revealed significant changes in two key parameters: the Green Chlorophyll Index (GCI) and Structure Insensitive Pigment Index (SIPI). The increase in both indices reflects improvements in the physiological and structural conditions of mangrove vegetation, which are directly related to the ecosystem's capacity to respond to environmental stress.

The Green Chlorophyll Index (GCI) showed a substantial rise from 1.14 in 2015 to 4.88 in 2025. This increase indicated higher chlorophyll accumulation in mangrove leaf tissues. Physiologically, it reflects an improvement in the photosynthetic process, which is a critical indicator of plant health and primary productivity. Ecologically, the increase in GCI also demonstrates the ability of mangrove ecosystems to respond to environmental pressures, both from natural factors, such as salinity, tidal fluctuations, and anthropogenic stressors. This trend may indicate successful natural regeneration, as well as the positive effects of rehabilitation programs implemented in coastal areas.

The Structure Insensitive Pigment Index (SIPI) also displayed an upward trend, rising from 0.84 in 2015 to 1.04 in 2025. This improvement reflects an enhanced vegetation structure, particularly in canopy thickness and the balance between photosynthetic and non-photosynthetic pigments. This balance is directly associated with the physiological stability of vegetation, showing that mangroves at the study site are becoming more efficient in carrying out photosynthesis and are more resilient to external stressors such as high salinity, tidal dynamics, and anthropogenic activities that may threaten mangrove ecosystems. **Table 1** presents the results of the vegetation index analysis for the periods 2020–2021 and 2024–2025, including the minimum, maximum, mean, and standard deviation values for each vegetation index.

Table 1. Vegetation index for the periods 2020–2021 and 2024–2025 (min, max, mean, and standard deviation).

No	Veg Index	2015				2020				2025			
		Min	Max	Mean	St Dev	Min	Max	Mean	St Dev	Min	Max	Mean	St Dev
1	NBR	-0.600	0.820	0.416	0.102	-0.587	0.857	0.418	0.105	-0.599	0.839	0.449	0.109
2	GCI	-1.200	8.500	1.14	1.900	-0.845	10.371	4.481	2.275	-0.858	11.924	4.883	2.4893
3	SIPI	-800	880	0.84	4.60	-755	919	1.039	4.937	-496	896	1.035	4.742
4	ARVI	-0.350	0.830	0.590	0.24	-0.303	0.865	0.607	0.258	-0.316	0.907	0.616	0.2637
5	NDVI	-0.680	0.900	0.690	0.298	-0.646	0.926	0.703	0.305	-0.607	0.951	0.707	0.3172

The results in **Table 1** show that the Green Chlorophyll Index (GCI) and the Structure Insensitive Pigment Index (SIPI) increased significantly and consistently between 2020 and 2021 and 2024–2025. The mean GCI increased from 4.481 to 4.883, reflecting higher chlorophyll content in mangrove leaves, which is directly linked to improved photosynthetic efficiency and higher primary productivity. A higher GCI also indicates an ecosystem's ability to respond to pressures from natural factors, such as salinity and tidal dynamics, as well as human activities. The SIPI increased slightly from 1.039 to 1.035, but higher values still reflected improvements in canopy thickness and pigment balance. This suggests a stronger physiological resilience of mangroves to salinity, tidal fluctuations, and anthropogenic pressure. They also showed better adaptation to extreme conditions. The Normalized Burn Ratio (NBR), Atmospherically Resistant Vegetation Index (ARVI), and Normalized Difference Vegetation Index (NDVI) remain stable from 2020 to 2025. NBR stability indicates no major degradation, ARVI confirms reliable remote sensing on humid coasts, and NDVI consistently reflects high vegetation density. The positive trends in the GCI and SIPI confirm that the mangrove ecosystem has undergone steady recovery during 2015–2025. Increases in chlorophyll content and vegetation structure demonstrate the overall improvement of ecological functions, including habitat provision, higher primary productivity, and enhanced blue carbon storage for climate change mitigation. Therefore, the GCI and SIPI can be regarded as reliable indicators for monitoring mangrove conservation and rehabilitation success.

3.4 Mangrove community structure

Based on observations in the Cikawung area in Sumur, the three stations exhibited different mangrove compositions. Station 1 was dominated by *Avicennia lanata* with the highest Importance Value Index (IVI) of 271.79, indicating significant density and dominance, whereas *Sonneratia lanceolata* acted only as an associate species with an IVI of 28.20.

Station 2 was dominated by *Avicennia officinalis* with an IVI of 300, reflecting a monospecific community that may be vulnerable to disturbances due to low heterogeneity. Station 3 was also monospecific and fully dominated by *Sonneratia lanceolata* (IVI 300), which demonstrates strong adaptation to muddy to sandy substrates.

The mangrove community structure in Cikawung showed distinct dominance across stations, with A. lanata at Station 1 and A. *officinalis* and S. *lanceolata* at Stations 2 and 3. The single-species dominance at the latter two stations indicates low species diversity, which poses a risk of reduced ecosystem function if disturbances occur. Pressures on mangrove ecosystems are unavoidable, considering the land conversion and current natural conditions that directly impact changes in mangrove coverage at several sites. Therefore, increasing species diversity through rehabilitation efforts is essential for maintaining the ecosystem stability in this area.

Fig. 3. Mangrove species composition at Cikawung Location (Station 1, Plot 1): *Avicennia lanata* and *Sonneratia lanceolata*.

3.5 Factors affecting mangrove health

The expansion of mangrove forests in the Sumur coastal area is influenced by both natural and anthropogenic factors. The dominant natural factor is the sedimentation process enriched with organic material, where river flow transports sediments from inland areas to the coast. Tidal dynamics provide suitable substrates for natural mangrove regeneration, accelerating the growth of pioneer species, such as Avicennia and Sonneratia, which play a key role in colonizing new areas. Anthropogenic factors also significantly influence mangrove health. Land conversion pressures for agriculture, aquaculture ponds, and coastal development pose major threats to mangrove sustainability. Land use change leads to habitat fragmentation, biodiversity loss, and reduced capacity of ecosystems to absorb blue carbon. Therefore, adaptive and conservation-based coastal spatial planning policies are essential for minimizing mangrove ecosystem degradation.

3.6 Impact of MHI monitoring for conservation and rehabilitation

Remote sensing–based analysis of the Mangrove Health Index (MHI) provides a clear spatiotemporal overview of mangrove ecosystem dynamics. Monitoring results showed that mangrove areas under effective conservation management recovered more rapidly, as indicated by significant increases in MHI values. Higher MHI scores reflected improvements in canopy structure, increased vegetation density, and greater chlorophyll content. MHI monitoring functions as both an indicator of vegetation conditions and a data-driven decision-making tool for conservation and rehabilitation strategies. Accurate information enables the identification of priority areas for rehabilitation, assessment of the effectiveness of replanting programs, and formulation of policies that adapt to ecosystem changes. Thus, a satellite imagery–based approach supported by field verification is an efficient strategy for maintaining the sustainability of mangrove ecosystems.

3.7 Challenges and recommendations

The increasing trend in mangrove ecosystem conditions within the study area demonstrates positive outcomes; however, several structural challenges remain. Pressures from land conversion and coastal infrastructure development pose the risk of reducing the extent of healthy mangrove areas. Global climate change, including sea-level rise, increasing temperatures, and shifting rainfall patterns, threaten the long-term stability of mangrove ecosystems.

Strategic recommendations include increasing the frequency of monitoring through a combination of high-resolution satellite imagery and field surveys to ensure accurate spatiotemporal data. Strengthened regulations and enforcement of coastal spatial planning are essential to limit unsustainable land conversion. Multistakeholder collaboration involving local governments, coastal communities, academics, and the private sector is required to reinforce conservation programs.

Local community participation is crucial because they are the direct users of mangrove ecosystems. An ecosystem-based management approach in coastal policy emphasizes the integration of ecological, social, and economic aspects to maintain a balance between resource utilization and conservation. The implementation of these recommendations will enable continued improvements in mangrove ecosystem health in the Sumur coastal area. Such improvements will support the sustainability of the blue economy and strengthen coastal resilience to climate change and anthropogenic pressures.

4 Conclusion

This study demonstrates that mangrove forests in the Sumur coastal area, Pandeglang, Banten, can be effectively monitored through spatio-temporal analysis of the Mangrove Health Index (MHI) using Sentinel-2 imagery. The results show an improvement from "moderate" in 2015 to "good" in 2025, with mangroves in very good condition expanding from 548.39 ha to 945.29 ha. The mangrove area has increased from approximately 3,500 ha to over 4,000 ha, supported by rehabilitation programs, stricter coastal regulations, and natural sedimentation.

Vegetation indices confirmed physiological and structural improvements, with GCI and SIPI showing significant increases, whereas NBR, NDVI, and ARVI remained stable. The community structure indicates low species diversity, highlighting the need for species diversification in rehabilitation. Natural sedimentation and anthropogenic pressures such as land conversion, coastal development, and climate change remain key challenges.

The Remote sensing–based MHI provides accurate, efficient, and applicable information for identifying priority areas, evaluating conservation programs, and supporting data-driven policies. Indicating the MHI based on remote sensing must be corrected by field observations because mangrove vegetation is sometimes mixed with non-mangrove vegetation.

Overall, mangrove ecosystems in Sumur have shown significant recovery over the past decade; however, long-term sustainability requires ecosystem-based management, stronger regulations, and multi-stakeholder collaboration to support a resilient blue economy in the Sunda Strait. Future research could design sustainable utilization of the mangrove ecosystem to empower the blue economy in the Sunda Strait.

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