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Spatio-Temporal Assessment of Mangrove Ecosystem Health Using an Integrated Mangrove Health Index (MHI) in Gusoh Pandang Bay, Southeast Sulawesi, Indonesia

Nazariano Rahman Wahyudi [a], *Fadil Apresia* [a]*

[a] *Faculty of Fisheries and Marine Science, Diponegoro University, Semarang City, Indonesia*
Jl. Prof. Soedarto, SH. Tembalang, Semarang 50275 Indonesia
Email: apresiafadilundip@gmail.com

A B S T R A C T

This study assesses the temporal dynamics of mangrove health in Gusoh Pandang Bay, Bombana Regency, Southeast Sulawesi, Indonesia, using Sentinel-2 satellite imagery and the Mangrove Health Index (MHI). The MHI synthesizes four vegetation indices: Normalized Burn Ratio (NBR), Green Chlorophyll Index (GCI), Structure Insensitive Pigment Index (SIPI), and Atmospherically Resistant Vegetation Index (ARVI). Sentinel-2 imagery from 2020, 2022, and 2024 was analyzed to identify changes in mangrove health. The results show relatively stable dynamics with a slightly positive trend. GCI and SIPI values indicate well-maintained physiological health and canopy cover. MHI-based classification reveals that the "Good" category consistently dominates, covering over 90% of the total area each year (95.9% in 2020, 92.2% in 2022, and 93.4% in 2024), reflecting overall ecosystem resilience. However, an increase in the "Poor" category from 1.44 hectares (2.1%) in 2020 to 2.80 hectares (4.1%) in 2024 suggests localized environmental pressures causing degradation in specific areas. The bay's semi-enclosed nature likely contributes to stable oceanographic conditions favorable for mangrove growth. The findings underscore the importance of integrating such remote-sensing assessments into coastal management frameworks. They highlight the need for continued monitoring and targeted conservation strategies within a proactive coastal management plan to maintain the long-term health and stability of the Gusoh Pandang Bay mangrove ecosystem.

Keywords: Mangrove Health Index, Sentinel-2, Remote Sensing, Geographic Information System, Coastal Management

1. Introduction

Mangrove forests are vital ecosystems in coastal regions, functioning as buffers, maintainers of ecological equilibrium, and foundations of the local economy. Indonesia plays a significant global role, contributing a total of three million hectares of mangroves. However, approximately 19.26%, or 637,624 hectares, of this area is in a critical state (Setyaningrum et al., 2022). This degradation is primarily attributed to land conversion for aquaculture, residential development, mining, and pollution, all of which jeopardize the ecosystem's functions as coastal protectors, blue carbon reservoirs, and habitats for diverse marine species.

Bombana Regency, located in Southeast Sulawesi, is characterized by its archipelagic geography, which renders it inherently vulnerable and simultaneously reliant on the vitality of its coastal ecosystems. The region's extensive coastline offers substantial potential in marine and fisheries resources, encompassing both capture fisheries and marine aquaculture sectors. Within this context, the mangrove ecosystem emerges as a critical component, encompassing an area of approximately ±6,053 hectares distributed across various subdistricts and coastal villages (Nur et al., 2022). The mangrove vegetation in this locale exhibits a tendency towards homogeneity, rendering it a consistent subject for research. Consequently, investigations into the condition of mangroves in Bombana are pertinent not only from an ecological standpoint but also in relation to the sustainable management of coastal resources. The presence of Gusoh Pandang Bay in this area is believed to harbor a significant mangrove ecosystem. Anthropogenic activities, such as fisheries and potential sedimentation from terrestrial sources, can impose stress on the mangrove ecosystem (Sutanto et al., 2022). Additionally, activities along the coast of Kabaena Island, which is abundant in nickel mineral resources, also pose potential environmental pressures, including impacts on the mangrove ecosystem (Taufik et al., 2021). These circumstances necessitate precise and ongoing monitoring, which is not only a scientific imperative but also a crucial basis for the planning of conservation and sustainable management of coastal areas in Bombana.

In the realm of monitoring extensive and frequently remote ecosystems such as mangroves, traditional methodologies like field surveys encounter substantial constraints regarding cost, time, and spatial coverage. Remote sensing technology presents a transformative solution. Sentinel-2 satellite imagery, characterized by its high spatial resolution (10 meters) and 13 spectral bands, has demonstrated efficacy in monitoring coastal environmental parameters(Lv et al., 2024). When integrated with satellite imagery data, Geographic Information System (GIS) technology can enhance detailed, contextual, and comprehensive analyses, thereby optimizing spatial analysis capabilities in identifying patterns, trends, and dynamics of environmental change (Xekalakis et al., 2025). To synthesize various spatial and spectral data into a comprehensive assessment, the Mangrove Health Index (MHI) serves as an appropriate methodology. MHI quantitatively amalgamates multiple biophysical indicators derived from satellite imagery, such as vegetation density (from the NDVI index), canopy condition, and the quality of surrounding waters, into a singular index representing the ecosystem's health status (Joshian Nicolas William Schaduw et al., 2024). This approach facilitates the spatially explicit identification of healthy, degraded, or critical mangrove areas.

There exists a discernible gap in the current body of knowledge, as no comprehensive mapping and Mangrove Health Index (MHI)-based health assessment have been conducted for the mangrove ecosystem in Gusoh Pandang Bay, Bombana Regency, utilizing the significant potential of Sentinel-2 imagery. This research seeks to address this gap, with the primary objective of mapping and evaluating the condition and health of mangrove forests in the bay through the application of the Mangrove Health Index approach, supported by an analysis of Sentinel-2 satellite imagery. The findings of this study are anticipated to provide a robust scientific database for local governments and stakeholders, facilitating the formulation of targeted policies and conservation strategies to protect this invaluable coastal resource.

2. Methodology

2.1 Study Location

The location of this study is the mangrove forest area in Teluk Gusoh Pandang, Bombana Regency, Southeast Sulawesi. This bay is situated on the southern coast of Sulawesi Island, directly facing the Flores Sea, and serves as an important area of interaction between terrestrial and marine ecosystems, with the study site shown in Figure 1. Hydrologically, the region is influenced by runoff from the hilly lands of Bombana, with land-based activities such as agriculture and the potential for sedimentation, both of which can affect mangrove health. This study was conducted by analyzing Sentinel-2 satellite imagery data in a time series, specifically during periods that represent the same seasonal conditions (to minimize seasonal bias) in 2020, 2022, and 2024, in order to identify the temporal dynamics and changes in mangrove health conditions.

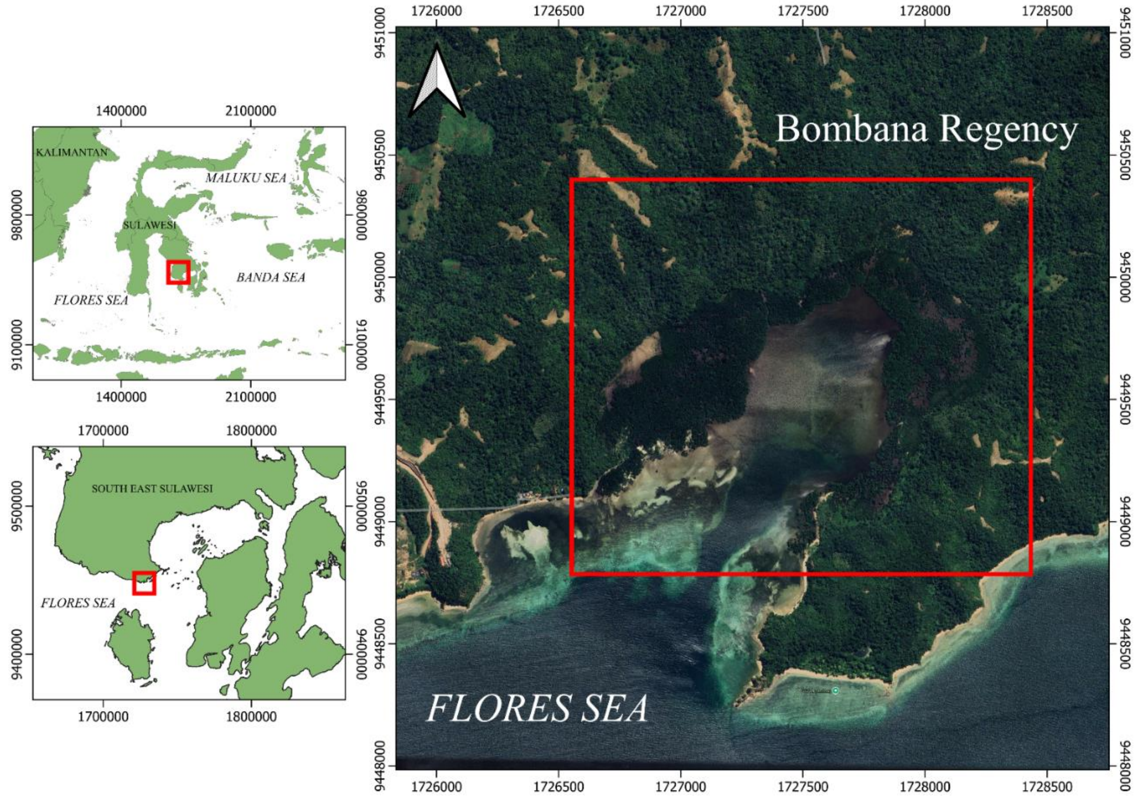

Fig. 1 – Study Area

2.2 Research Data

This study utilizes primary data derived from Sentinel-2 satellite imagery at processing level 1C (Level-1C), captured during three distinct periods: 2020, 2022, and 2024. At the 1C processing level, Sentinel-2 imagery has undergone fundamental radiometric correction, wherein pixel digital values are converted to top-of-atmosphere reflectance, alongside geometric correction to ensure a standardized coordinate and projection system. The Sentinel-2 satellite is equipped with a multispectral instrument that records data across 13 spectral bands, each exhibiting unique spatial resolution characteristics. This configuration includes four bands with the highest spatial resolution of 10 meters, generally encompassing the visible and near-infrared spectrum.

Additionally, six bands possess a spatial resolution of 20 meters, covering the red-edge and short-wave infrared spectral channels, which are particularly beneficial for vegetation characterization. Lastly, three bands have a spatial resolution of 60 meters, typically employed for atmospheric correction and aerosol detection. The integration of these varying resolutions facilitates comprehensive analysis, allowing for the combination of high spatial detail with rich spectral information, thereby enhancing the accuracy of mangrove cover identification and classification.

2.3 Mangrove Health Index (MHI) Analysis

The Mangrove Health Index (MHI) is derived from an integration of four distinct vegetation indices, each sensitive to specific aspects of vegetation condition. These indices include the Normalized Burn Ratio (NBR), which is typically employed to detect changes associated with fire or severe vegetation stress; the Green Chlorophyll Index (GCI), which is particularly responsive to chlorophyll content in leaves; the Structure Insensitive Pigment Index (SIPI), designed to minimize the influence of canopy structure and thereby emphasize pigment content information; and the Atmospherically Resistant Vegetation Index (ARVI), an enhancement of the NDVI that offers superior atmospheric correction, rendering it more resistant to aerosol interference (Alina et al., 2025). The integration of these four indices was selected to provide a more comprehensive and robust assessment of mangrove ecosystem health compared to the use of a single index. Validation of the efficacy of this integration in determining the MHI parameters is necessary. In the relevant study, the pixel values of satellite imagery resulting from the combination of the four vegetation indices demonstrated a very strong statistical correlation with the ecological condition of the mangroves (Nurdiansah & Dharmawan, 2021). The detailed calculation formulas are described in the following section.

$$NBR = \frac{(NIR - SWIR)}{(NIR + SWIR)} \quad (1)$$

$$GCI = \frac{(NIR)}{(GREEN - 1)} \quad (2)$$

$$SIPI = \frac{(NIR - BLUE)}{(NIR - RED)} \quad (3)$$

$$ARVI = \frac{(NIR - 2RED + BLUE)}{(NIR + 2RED + BLUE)} \quad (4)$$

$$MHI = 102.12NBR - 4.64GCI - 179.15SIPI - 159.53ARVI - 252.39 \quad (5)$$

Based on the value of the Mangrove Health Index (MHI), the condition of the mangrove forest is classified into three main categories. This classification follows the thresholds established in the reference study, namely: poor condition for MHI values below 33.3%; moderate condition for MHI values between 33.4 and 66.7; and good condition for MHI values above 66.8 (Wayan Eka Dharmawan, 2021).

3. Results and Discussion

The calculation of the Mangrove Health Index (MHI) in this study is derived from the synthesis of four specific vegetation indices that represent different aspects of mangrove health. These four indices are: the Normalized Burn Ratio (NBR), which is sensitive to changes in biomass and stress; the Green Chlorophyll Index (GCI) as an indicator of chlorophyll content; the Structure Insensitive Pigment Index (SIPI), which is relatively unaffected by canopy structure and is thus effective for estimating pigments; and the Atmospherically Resistant Vegetation Index (ARVI), which has been corrected for the effects of aerosol scattering in the atmosphere. Each of these indices was analyzed separately for each observation period—2020, 2022, and 2024—using processed Sentinel-2 satellite imagery. The numerical results of each mangrove vegetation index for these three years are presented in full in Table 1, Average Value of Mangrove Vegetation Index from Satellite Imagery Analysis. The analysis of all four vegetation indices shows relatively stable dynamics from 2020 to 2024, with most indices exhibiting a very moderate upward trend. For the NBR index, the average value increased slightly from 0.48 ± 0.17 in 2020 to 0.50 ± 0.17 in 2022, and remained at the same value (0.50 ± 0.17) through 2024. A similar pattern is also seen in the ARVI index, which remained consistent from 0.62 ± 0.22 (2020), 0.62 ± 0.25 (2022), to a slight increase of 0.63 ± 0.24 in 2024. Meanwhile, the other two indices—although they did not show marked changes—still indicate the stable condition of mangrove vegetation. The GCI value shifted from 5.03 ± 2.41 (2020) to 5.00 ± 2.57 (2022), then increased slightly to 5.11 ± 2.52 in 2024. The SIPI index also showed an almost identical pattern, with values of 1.03 ± 0.14 in 2020, a slight decrease to 1.01 ± 0.44 in 2022, then a modest rise to 1.02 ± 0.67 in 2024. According to the literature, stable or slightly increased SIPI and GCI values may reflect a relatively well-maintained mangrove canopy cover and density throughout the observation period(Chaube et al., 2019). This finding is consistent with the results of the spatial analysis, which showed that the mangrove forest area in the study site did not experience significant reduction and tended to remain stable over the 2020–2024 period. The finding regarding the stability of mangrove health in Gusoh Pandang Bay is in line with several other studies in Indonesia that use a similar MHI approach. A study in Bunaken National Park, for example, also reported that most mangrove areas were in good to very good condition, with only a small portion categorized as less healthy(Schaduw et al., 2024). The stability of vegetation index values, particularly GCI and SIPI—which indicate the physiological health of leaves—may well be supported by the stability of key water parameters such as salinity and temperature. Mangroves have a certain range of salinity tolerance, and extreme fluctuations can lead to osmotic stress(Parida & Jha, 2010). Gusoh Pandang Bay, as a relatively semi-enclosed body of water, may have stable water dynamics. Good but not overly energetic water circulation (i.e., no large waves) can maintain optimal salinity conditions for mangrove growth without causing excessive physical stress to the roots. The stability of sea surface temperatures recorded from satellite data during the study period may also contribute to the minimal thermal stress experienced by the vegetation(Chen et al., 2017).

Table 3. Summary of the results of extracting vegetation index values from satellite images for the observation periods 2020, 2022, and 2024.

Index	**2020**				**2022**				**2024**			
	Mean	**Min**	**Max**	**St Dev**	**Mean**	**Min**	**Max**	**St Dev**	**Mean**	**Min**	**Max**	**St Dev**
Normalized Burn Ratio (NBR)	0.48	-0.46	0.71	0.17	0.50	-0.39	0.72	0.17	0.50	-0.45	0.72	0.17
Green Chlorophyll Index (GCI)	5.03	-0.93	11.74	2.41	5.00	-0.88	11.37	2.57	5.11	-0.94	11.07	2.52
Structure Insensitive Pigment Index (SIPI)	1.03	-3.00	5.22	0.14	1.01	-31.00	6.00	0.44	1.02	-22.75	42.00	0.67
Atmospherically Resistant Vegetation Index (ARVI)	0.62	-0.32	0.88	0.22	0.62	-0.35	0.88	0.25	0.63	-0.31	0.87	0.24

The Mangrove Health Index (MHI) is derived by synthesizing four vegetation indices—NBR, GCI, SIPI, and ARVI—into a singular composite numerical model, thereby producing an integrative and comprehensive health map. This methodology is predicated on the recognition that the health of mangrove ecosystems is a multidimensional construct, encompassing biomass, physiological vitality, pigment content, and resilience to atmospheric disturbances. The selected combination of indices is intended to more comprehensively capture this complexity, rendering the MHI a more robust indicator than any single index. The culmination of this integration process is a spatial distribution map of the MHI for each observation year, which visually delineates the spatial patterns of mangrove health and their temporal dynamics from 2020 to 2024, as depicted in Figure 2, Figure 3, and Figure 4 below.

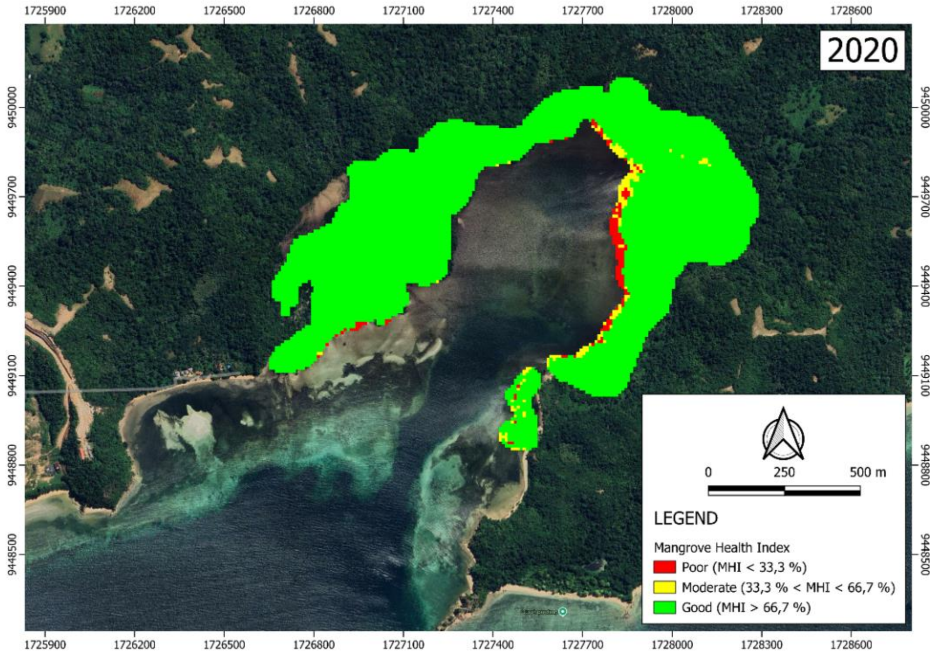

Fig. 2 – Mangrove Health Map (MHI) of Gusoh Pandang Bay, Bombana, Southeast Sulawesi in 2020 from Sentinel-2 Imagery

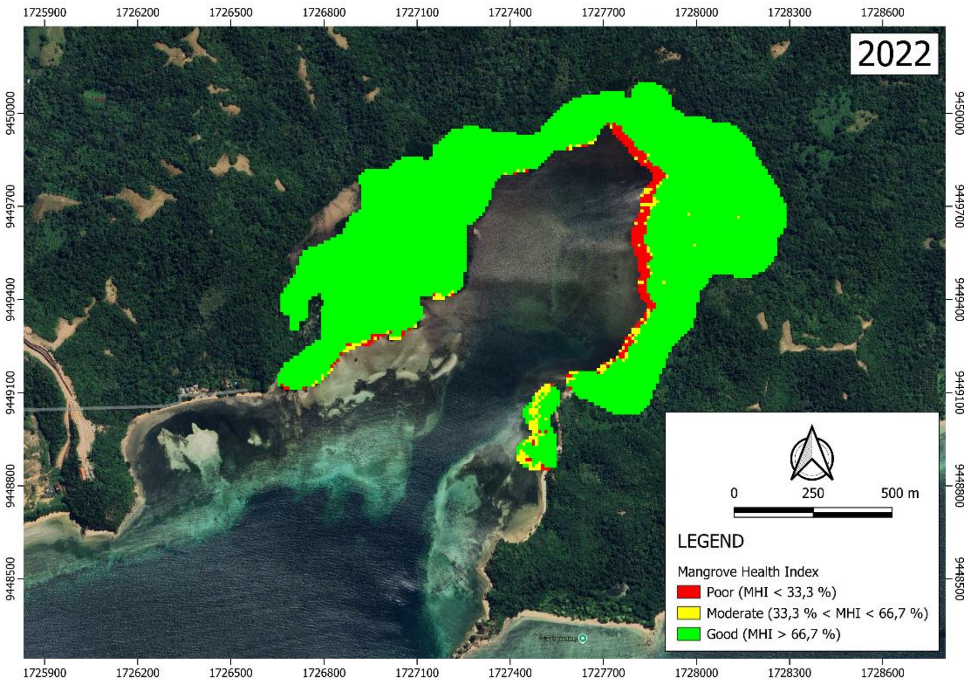

Fig. 3 – Mangrove Health Map (MHI) of Gusoh Pandang Bay, Bombana, Southeast Sulawesi in 2022 from Sentinel-2 Imagery

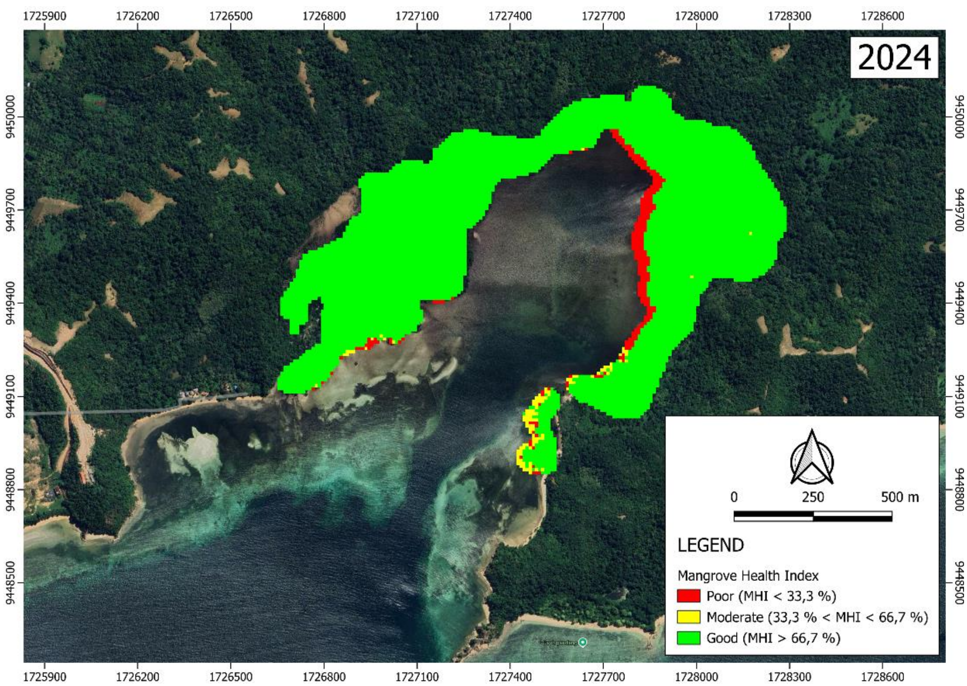

Fig. 4 – Mangrove Health Map (MHI) of Gusoh Pandang Bay, Bombana, Southeast Sulawesi in 2024 from Sentinel-2 Imagery

According to the findings of the 2020 analysis, the health status of the mangroves was predominantly classified as good, encompassing an area of 64.77 hectares, which constitutes approximately 95.9% of the total classified area. The medium classification represented only 1.56 hectares (2.3%), while the poor classification accounted for 1.44 hectares (2.1%). This distribution suggests that at the commencement of the observation period, the mangrove ecosystem was in a relatively healthy state, characterized by vegetation cover dominated by a high-quality canopy.

In 2022, there was a notable shift in the composition of health classes. The area classified as "good" experienced a slight decrease, encompassing 63.25 hectares (92.2%), while the "moderate" category increased to 1.84 hectares (2.7%). Conversely, the "poor" category rose significantly to 2.67 hectares (3.9%). This increase in the "poor" category suggests the presence of environmental pressures or local disturbances that have adversely affected vegetation quality in certain areas. Nonetheless, the overall condition of the mangroves predominantly remains within the "good" category.

In 2024, the health status of mangroves has once again exhibited variability. The area classified as being in good condition has slightly increased to 63.91 hectares (93.4%), indicating stabilization or recovery of vegetation in certain regions. Conversely, the area categorized as moderate has decreased to 1.06 hectares (1.5%), while the area classified as poor has risen to 2.80 hectares (4.1%). The reduction in the moderate category, coupled with an increase in the poor category, suggests that a small portion of mangrove areas has experienced further degradation, although the extent remains relatively minor compared to the total area.

The persistent and predominant presence of the Good class, consistently exceeding 90% (ranging from 95.9% to 93.4%), suggests that the fundamental oceanographic conditions in Teluk Gusoh Pandang are generally conducive. The bay's relatively sheltered nature, being semi-enclosed, is posited to foster a stable physical environment characterized by low wave energy, minimal salinity fluctuations, and adequate sedimentation rates. These conditions are highly favorable for mangrove growth and resilience, as they safeguard root systems from excessive erosion and ensure substrate stability(Ndirangu et al., 2017). This stability is evidenced by the predominance of the Good class. However, there was a notable increase in the area classified as Poor, from 1.44 ha in 2020 to 2.67 ha in 2022, accompanied by a reduction in the Good class. More intense dry seasons or alterations in freshwater flow patterns from land can elevate local salinity in certain bay areas. Salinity levels outside the optimal tolerance range for mangroves can induce osmotic stress, inhibit photosynthesis, and cause leaf yellowing (chlorosis), thereby relegating those areas to lower health classes(Barnuevo & Asaeda, 2018). Overall, the dynamics of mangrove health class distribution during the 2020–2024 period demonstrate that the Good category consistently remains the dominant class, maintaining a proportion exceeding 90% annually. Nonetheless, fluctuations in the moderate and poor classes indicate that certain areas remain susceptible to ecological stressors, necessitating ongoing monitoring and more sustainable management. The spatial transitions between these classes highlight the importance of conservation strategies to preserve the stability of the mangrove ecosystem in the study area.

4. Conclusion

Synthesis of the four vegetation indices (NBR, GCI, SIPI, ARVI) that make up the Mangrove Health Index (MHI) shows relatively stable dynamics with a moderately positive trend. The index values related to chlorophyll content (GCI) and canopy pigmentation (SIPI) indicate that the physiological health and canopy cover of the mangroves are well maintained. Health classification based on the MHI reveals that the "Good" category absolutely dominates every year, consistently covering over 90% of the total area (95.9% in 2020, 92.2% in 2022, and 93.4% in 2024). This reflects the overall resilience of the mangrove ecosystem. Although the "Good" category dominates, the study detected an increase in the area classified as "Poor," from 1.44 hectares (2.1%) in 2020 to 2.80 hectares (4.1%) in 2024. Fluctuations in the "Moderate" and "Poor" categories indicate the presence of localized and specific environmental pressures in certain parts of the bay, leading to degradation in those areas. The stability of mangrove health is strongly suspected to be supported by the relatively stable oceanographic conditions of Gusoh Pandang Bay. The semi-enclosed shape of the bay is thought to create a physical environment with low wave energy, limited fluctuations in salinity, and stable sea surface temperatures. These conditions are optimal for mangrove growth, as they protect root systems from excessive erosion and minimize physiological stress. The study's findings emphasize that even in a healthy state, the mangrove ecosystem in this bay is not immune to disturbances. The increase in the area under the "Poor" category serves as an early warning signal. Therefore, continuous monitoring using a similar approach is highly necessary to identify long-term trends and vulnerable points of degradation. The results of this study can serve as a scientific basis for formulating focused management and conservation strategies (such as restoration of specific degraded plots) to maintain the stability and overall health of the mangrove ecosystem in Gusoh Pandang Bay in the future.

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