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Assessment of spatio-temporal dynamics of mangrove forest in Teluk Pangpang, Banyuwangi, East Java, Indonesia

ZAINUL HIDAYAH[1,♥], HERLAMBANG AULIA RACHMAN[1], DWI BUDI WIYANTO[2]

[1]Department of Marine Science and Fisheries, Faculty of Agriculture, Universitas Trunojoyo Madura. Jl. Raya Telang No. 2, Kamal, Bangkalan 69162, East Java, Indonesia. Tel.: +62-31-3011146, Fax.: +62-31-3011506, ♥email: zainulhidayah@trunojoyo.ac.id

[2]Department of Marine Science, Faculty of Marine and Fisheries, Universitas Udayana. Kampus Bukit Jimbaran, Jl. Raya Kampus UNUD, Badung 80361, Bali, Indonesia

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Abstract. *Hidayah Z, Rachman HA, Wiyanto DB. 2024. Assessment of spatio-temporal dynamics of mangrove forest in Teluk Pangpang, Banyuwangi, East Java, Indonesia. Biodiversitas 25: 3138-3150.* Mangrove forest in Teluk Pangpang, Banyuwangi District, East Java, Indonesia is located in a semi-enclosed bay area on the east coast of Java Island and bordering with Bali Strait. Since 2020, this location has been designated as an Essential Ecosystem Area (EEA) by the Indonesia Ministry of Environment and Forestry. Regardless of its designation as an EEA, information on vegetation stucture and spatio-temporal changes of Teluk Pangpang's mangrove forest is limited. The availability of multi-temporal medium to high-resolution satellite imagery data enables researchers to monitor the condition of mangrove ecosystem using long-term data and reliable spatial continuity. The objective of this study is to investigate vegetation community structure of mangrove forest in Teluk Pangpang, as well as to determine the changes in extent and condition of mangrove forest measured as Mangrove Health Index (MHI) between 2015 and 2023 using remote sensing and GIS analysis. Spatio-temporal dynamics of MHI was determined using Sentinel-2 imagery data from 2015, 2018 and 2023. Meanwhile, a series of extensive survey in 15 transects with a total of 75 plots were conducted to obtain field data. The results showed that *Rhizophora apiculata* Blume and *R. mucronata* Lam. were the most important species with Important Value Index (IVI) of 140.91 and 148.24, respectively. Meanwhile, Sentinel-2 image processing results revealed a major increase in mangrove's area, from 643.35 ha in 2015 to 737.51 ha in 2023. Furthermore, MHI analysis indicated improving conditions of mangrove ecosystem, as evidenced by the significant increased of mangroves area at the excellent MHI category (MHI>66.8) from 11.00 ha in 2015 to 175.86 ha in 2023. Based on Principal Component Analysis (PCA) several environmental parameters were strongly correlated to MHI including salinity, DO, TSS and mangrove's diversity index. The findings of this study, primarily the application of MHI approach, may provide an alternative strategy for monitoring the dynamics of vegetation cover of mangrove forest in Teluk Pangpang and other mangrove areas in Indonesia.

Keywords: Mangrove health index, Sentinel-2, spatio-temporal dynamic, Teluk Pangpang

INTRODUCTION

Mangroves form distinctive wetland ecosystem occurring primarily in the intertidal zone of tropical and subtropical regions. This ecosystem is characterized by salt-tolerant woody vegetation with extensive root systems that provide growth stability on the muddy substrate of river estuaries, delta plains, or semi-closed coastal areas (Hu et al. 2020; Toosi et al. 2022). Mangroves serve many ecological functions including protecting coastlines from erosion and abrasion, filtering coastal water, preventing seawater intrusion, serving as feeding and nursery ground for aquatic and benthic species and sequestering a significant amount of carbon (Nagelkerken et al. 2008; Hutchison et al. 2014; Srikanth et al. 2016; Woodroffe et al. 2016).

Despite their great importance, mangrove ecosystems globally are pressured by various factors. Between 1996 to 2020 mangrove area worldwide has decreased from 15.26 million ha to 14.73 million ha (Bunting et al. 2022) with estimated loss rate is approximately 21,854 ha $year^{-1}$. Southeast Asia's mangrove area covering 32.7% of the global mangrove area in 2020. However, this region has suffered the most significant net loss with an estimated area of 245,560 ha, accounting for 47% of the global net loss in total. During the same time period, mangrove area in Indonesia has decreased by 174,000 ha, from 3.12 million ha in 1996 to 2.95 million ha in 2020 (Bunting et al. 2022; Hidayah et al. 2022).

Understanding current state and temporal changes of mangrove ecosystem are important for its sustainable management, conservation and rehabilitation (Hidayah et al. 2024). In doing so, field observations as conventional method are required to obtain ecological status of a mangrove ecosystem. However, mangrove forests are generally situated in challenging environments. The combination of thick sediment, dense stands with complex root systems, in addition to remoteness and inaccessibility of some areas, makes extensive sampling and monitoring impractical and extremely resource-intensive (English et al. 1997). To address these issues, Geographic Information Systems (GIS) analysis and remote sensing technology has been proven to be an effective instrument for monitoring vast area of mangrove forests (Nguyen et al. 2019; Purwanto and Asriningrum 2019).

Several parameters can be used for evaluating the condition of mangrove ecosystem, including spesies diversity, vegetation density, canopy cover, and biomass (Aminuddin et al. 2019; Singh 2020). When using satellite imagery data, the condition of a mangrove ecosystem is typically assessed using a variety of vegetation indices. Various algorithms were developed from the combination of spectral bands to estimate mangrove biomass and carbon stock (Bao et al. 2022; Hidayah et al. 2022; Suardana et al. 2023). Presently, research on the use of remote sensing technology to monitor mangrove forests has mainly focused on changes in area (Mohd-Razali et al. 2020; Long et al. 2021). However, there have been few studies focus on changes in the health of mangroves. The health status of mangroves according to field conditions can be determined using three main parameters of mangrove's stand structure namely stem diameter, canopy cover, and density (Prasetya et al. 2017; Schaduw et al. 2021). Further studies have modelled the Mangrove Health Index (MHI) on a particular geographical extent and have discovered to be highly correlated with a combination of several vegetation indices obtained from remote sensing analysis (Sugiana et al. 2022). A combination of vegetation indices used to calculate MHI including NBR (Normalized Burn Ratio), GCI (Green Chlorophyll Index), SIPI (Structure Insensitive Pigment Index) and ARVI (Atmospherically Resistant Vegetation Index) (Dharmawan 2021). This index must continue to be tested and evaluated for reliability and relevance to field conditions.

East Java Province of Indonesia has 27,221 ha of mangroves or 48% of total mangrove forests in Java Island (Rudianto et al. 2020; Hidayah et al. 2024). Since 2020, the Ministry of Environment and Forestry has established two mangrove forests in this province, namely in Ujung Pangkah and Teluk Pangpang, as Essential Ecosystem Areas (EEAs). This initiative is part of government's efforts to preserve wetland areas according to the Ramsar Convention, a UN-initiated convention that establishes a framework for the conservation and wise use of wetlands. Despite its designated purposes, information on the community structure and spatio-temporal changes of mangrove vegetation in Teluk Pangpang, is limited. Given this background, the goal of this research is to investigate the condition of the mangrove ecosystem using vegetation community structure parameters, as well as to determine the MHI spatiotemporal change of the mangrove forest in Teluk Pangpang. This study's findings are expected to provide scientifically based data for sustainable regional planning and conservation policies of East Java's mangrove forest ecosystem.

MATERIALS AND METHODS

Study period and area

This study was conducted from August to December 2023 at mangrove forest in Teluk Pangpang in Banyuwangi District, East Java Province, Indonesia, located at 08°32'15,745"S and 114°21'41,807"E. Teluk Pangpang is a semi-enclosed bay area on the east coast of Java Island boredered with Bali Strait to the East (Figure 1). The dominant land cover in the study location was characterized by dense mangrove vegetations with typical sandy clay subtrates. Aquaculture in the form of fish ponds and shrimp ponds were found scattered adjacent to the mangroves. The morphology of Teluk Pangpang is a typical flat beach with slope around 0-5º dominated by homogenous soil condition. The tidal type in Teluk Pangpang is mixed semidiurnal tide with a mean sea level of 0.02 meters and a tidal range reaching 0.83 meters. Various species of crustaceans occurred in Teluk Pangpang Mangrove Forest included several species of shrimp *Litopenaeus vannamei* (Boone, 1931) or king prawn, mud crab (*Scylla serrata* (Forskål, 1775)) and blue swimming crab (*Portunus pelagicus* (Linnaeus, 1758)) (Rodiana et al. 2019). Teluk Pangpang Mangrove Forest also serves as a stopping point for migratory birds from Australia during certain seasons, particularly October-December. According to the East Java Natural Resources Conservation Center (*Balai Besar Konservasi Sumber Daya Alam/BKSDA*), at least 20 different species of migratory birds visit or live in the Teluk Pangpang Mangrove Forest.

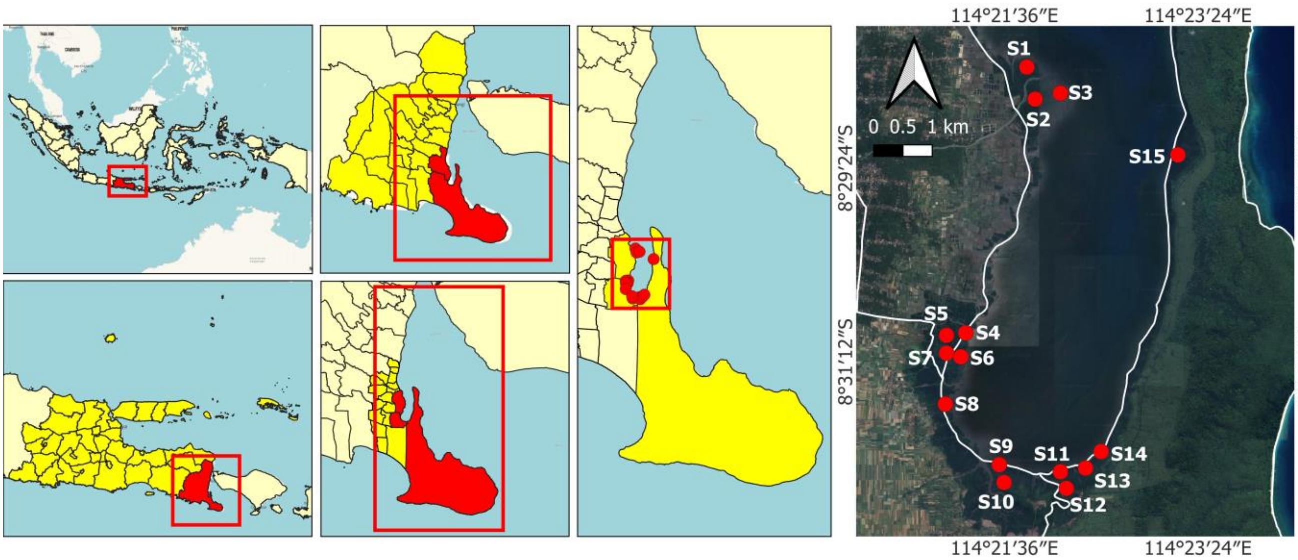


Figure 1. Map of study area at mangrove forest in Teluk Pangpang, Banyuwangi District, East Java Province, Indonesia

Field data collection

A series of field data collection were conducted using standard procedure for mangrove survey adapted from English et al. (1997). A total of fifteen 100-meter-long transect lines were placed perpendicular to the coastline across mangrove forests. This study was focused on rapid diversity assessment and did not take into account mangrove forest zonation patterns. Three quadrati plots with size of 10×10 m each were placed 50 m apart along each transect line, resulting in 75 sampling plots in total. Individual species names were recorded, and Diameters at Breast Height (DBH) were measured. Sampling locations were carefully selected based on accessibility and representativeness of the entire mangrove forest area. Mangroves species were identified based on the physical appearance of roots, leaves, fruits or propagules using mangrove's identification guidebook (Giesen et al. 2007). Water quality parameters including salinity, temperature, pH, Dissolved Oxygen (DO) and Total Suspended Solid (TSS) were also measured in-situ using HORIBA water checker instrument. The geographical coordinates of all transects/stations are presented in Table 1.

Calculation of Important Value Index (IVI)

Mangrove's vegetation structure were determined using Important Value Index (IVI). This index indicates the representativeness of certain mangrove species in the ecosystem and it ranges between 0-300 (English et al. 1997). The IVI of each mangrove species was calculated by adding the relative frequency, density, and dominance values. The index was calculated for each transect using these formulas:

$$Di = \frac{ni}{A}\ ; \quad RDi = \left[\frac{ni}{\sum n}\right] \times 100 \qquad \text{.............................. (1)}$$

Where:
Di : Species-i density
RDi : Relative density of species-i
ni : Total number of species-i
Σn : Total number of all species
A : Total sampling area (300 m^2)

$$Fi = \frac{pi}{\sum F};\quad RFi = \left[\frac{Fi}{\sum F}\right] \times 100 \qquad \text{.............................. (2)}$$

Where:
Fi : Species-i frequency
RFi : Relative frequency of species-i
pi : Number of plot where species-i found
∑F : Total number of plots in each transect (3)

$$Ci = \frac{\sum BA}{A};\quad RCi = \left[\frac{Ci}{\sum C}\right] \times 100 \qquad \text{........................... (3)}$$

Where:
Ci : Species-i coverage
RCi : Relative coverage of species-i
∑BA : $\pi d^2/4$ (π = 3,14: d = DBH)
∑C : Total coverage for all species
A : Total sampling area (300 m^2)

$$IVI = RDi + RFi + RCi \qquad \text{..................................... (4)}$$

In order to provide a more comprehensive description of mangrove community stucture of Teluk Pangpang species richness was determined using Shannon-Wiener Diversity Index (H'). Diversity Index H' is classified as follows: low diversity (H'<1), moderate diversity (1<H'≤3), and high diversity (H'>3). The calculation of H' uses the following equation (Odum 1993).

$$H' = \sum Pi\ Ln\ Pi;\quad Pi = \left(\frac{ni}{N}\right) \qquad \text{............................. (5)}$$

Where:
H' : Shannon-Wienner Index
ni : Density of the each species
N : Total density of all species

Additionally, the Evenness Index of species Pielou (J) was calculated to describe the level of each species' distribution. The value of J is classified into three categories, including low species evenness (J<0.03), moderate species evenness (0.3<J<0.6), and high species evenness (J>0.6). The calculation of J uses the following equation (Odum 1993)

$$J = \frac{H'}{Ln\ S} \qquad \text{... (6)}$$

Where:
J : Species evenness index
S : Total number of species
H' : Species diversity index

Another ecological index used in this study is the species Dominance Index (D), which was calculated to measure domination by specific species. The dominance index ranges between 0 and 1. The lower the dominance index value, the fewer dominant species exist; otherwise, the higher the dominance, the more dominant species are present.This index is calculated by using the following formula (Odum 1993).

$$D = \sum \left(\frac{ni}{N}\right)^2 = \sum Pi^2 \qquad \text{.................................... (7)}$$

Where:
D : Dominance index
ni : Density of the each species
N : Total density of all species

Satellite image processing

This study used three sets of medium resolution Sentinel-2 level 1C images acquired in 2015, 2018 and 2023. At level 1C, the Sentinel 2B satellite image has been radiometrically corrected. The Sentinel-2 satellite was launched in 2015 as part of the European Space Agency's (ESA) Copernicus program. The main task of this satellite is to monitor changes in land use and land cover, particularly in agricultural and forest areas. Sentinel satellite imagery can also be used to monitor and map biophysical variables in terrestrial and coastal environments (Kawamuna et al. 2017). The Sentinel-2 image contains 13 bands, four with a resolution of 10 meters, six with a resolution of 20 meters, and three with a resolution of 60 meters (Table 2).

Table 1. Geographical coordinates of transect lines/stations established at mangrove forest in Teluk Pangpang, Banyuwangi District, East Java Province, Indonesia

Stations	Latitude (S)	Longitude (E)
S1	8°28'27,52"	114°21'48,49"
S2	8°28'45,38"	114°21'53,17"
S3	8°28'42,07"	114°22'07,22"
S4	8°30'55,70"	114°21'14,38"
S5	8°30'57,02"	114°21'03,68"
S6	8°31'08,93"	114°21'11,70"
S7	8°31'06,95"	114°21'03,68"
S8	8°31'35,39"	114°21'03,01"
S9	8°32'09,13"	114°21'33,11"
S10	8°32'19,05"	114°21'35,78"
S11	8°32'13,09"	114°22'07,22"
S12	8°32'22,35"	114°22'10,56"
S13	8°32'11,11"	114°22'21,27"
S14	8°32'01,85"	114°22'29,96"
S15	8°29'16,47"	114°23'12,77"

Table 2. Spectral and spatial characteristics of Sentinel-2 imagery data

Bands	Wave lenght (µm)	Spatial resolution (m)
Band-1 Coastal Aerosol	0.433-0.453	60
Band 2- Blue	0.458-0.523	10
Band 3- Green	0.543-0.578	10
Band 4- Red	0.650-0.680	10
Band 5- Vegetation Red Edge	0.698-0.713	20
Band 6- Vegetation Red Edge	0.733-0.748	20
Band 7- Vegetation Red Edge	0.765-0.785	20
Band 8- NIR	0.758-0.900	10
Band 8A- Vegetation Red Edge	0.855-0.875	20
Band 9- Water Vapour	0.930-0.950	60
Band 10- SWIR Cirrus	1.365-1.385	60
Band 11- SWIR	1.565-1.655	20
Band 12- SWIR	2.100-2.280	20

Source: Sentinel-2 User's Guide (https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-2-msi/overview)

To identify mangrove vegetation, supervised classification based on Normalized Difference Vegetation Index (NDVI) was conducted. The classification was divided into two classes: mangrove and non-mangrove. The training and validation data for this study were obtained from very high spatial resolution images in the 2022 Google Earth Pro imagery. The NDVI formula for a Sentinel-2 satellite image was analysed as follow:

$$NDVI = \frac{Near\ Infra\ Red\ Band - Red}{Near\ Infra\ Red\ Band + Red} \quad \text{.................. (8)}$$

Spatial analysis of Mangrove Health Index

The Mangrove Health Index (MHI) value was determined based on the combination of 4 vegetation indices, namely Normalized Burn Ratio (NBR); Green Chlorophyll Index (GCI); Structure Insensitive Pigment Index (SIPI) and Atmospherically Resistant Vegetation Index (ARVI). Based on research conducted by Nurdiansah and Dharmawan (2021), the pixel value of the Sentinel image resulting from a combination of the four vegetation indices has a high correlation value (r = 0.831) with the ecological condition of mangroves which is determined based on the parameters of canopy cover, sapling density and diameter of mangrove vegetation. The vegetation index formula used and the MHI calculation using Sentinel-2B satellite imagery are shown by the following equations (Dharmawan 2021):

$$NBR = \frac{(NIR - SWIR)}{(NIR + SWIR)} \quad \text{.. (9)}$$

$$GCI = \frac{NIR}{(Green - 1)} \quad \text{.. (10)}$$

$$SIPI = \frac{(NIR - Blue)}{(NIR - Red)} \quad \text{.. (11)}$$

$$ARVI = \frac{(NIR - 2Red + Blue)}{(Nir + 2Red + Blue)} \quad \text{.......................... (12)}$$

$$MHI = 102{,}12\ NBR - 4{,}64\ GCI + 178{,}15\ SIPI + 159{,}53\ ARVI - 252{,}39 \quad \text{...(13)}$$

The condition of mangrove forests based on the MHI can be categorized into 3 classes, namely poor (MHI<33.3%), fair/moderate (33.4<MHI<66.7) and excellent (MHI>66.8). The minimum MHI value was found to be 18% using the original formula because lower amounts indicate that it had no more vegetation. Rehabilitation potential area was categorized into 0 to 18% of MHI value as a shallow habitat for mangrove seedling or a post-dieback area (Sugiana et al. 2022).

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was used in this study to further investigate the relationship and characteristics of MHI resulted from satellite image processing with several ecological parameters. This method is a type of multivariate analysis that is used to summarize data from multiple variables while searching for patterns of relationships between them. In addition, another benefit of PCA analysis is the visualization of results, which can explain attribute clusters, trends, and outliers in the variables studied (Marpaung et al. 2022). In this study, PCA was used to investigate the correlation of MHI produced by satellite image processing with several ecological and water quality parameters. Additionally, PCA could provide more information about the characteristics of MHI classification in relation to field conditions.

RESULTS AND DISCUSSION

The dynamics of mangrove extent in Teluk Pangpang

The spatial analysis of Sentinel-2 satellite imagery data reveals the dynamics of mangrove forest in Teluk Pangpang from 2015 to 2023. The result shows a trend toward positive conditions, notably an increase in the area of mangroves. The area of mangrove forests at this location was 645.35 ha in 2015, and increased to 680.44 ha in 2018. Furthermore, the analysis results for 2023 show an increase of approximately 57 ha, adding the total area of mangrove forest to 737.51 ha (Figure 2). The positive trend indicates that the natural mangrove forest ecosystem is not subjected to environmental pressure and disturbance from destructive anthropogenic activities, even though Teluk Pangpang aquatic environment is heavily used for fisheries and mariculture activities. This cannot be separated from the high level of public awareness of the importance of mangrove forests, as well as the designation of Teluk Pangpang Mangrove Forest as an Essential Ecosystem Area (EEA) and buffer zone for Alas Purwo National Park.

Mangroves extent and distribution in Teluk Pangpang was determined using NDVI (Figure 2). This vegetation index is measured based on the absorption in the red spectrum and very strong reflectance in the near infrared spectrum of Sentinel-2 bands. Previous studies have reported strong correlation between NDVI and canopy cover of mangrove vegetations (Umroh et al. 2016; Baniya et al. 2018; Suwanto et al. 2021). Therefore, NDVI is widely used to quantify mangrove forest's density (Zhang et al. 2016; Roy et al. 2019; Long et al. 2021). The higher the NDVI value, the denser the vegetation. In addition of detecting an increase in mangrove area, Sentinel-2 image analysis in this study revealed improvements in the condition of the mangrove forest. In particular on the west side of the area, in 2015 mangroves with low density (NDVI<0.3) appeared to dominate, but this condition improved substantially in 2018. Hence in 2023 the density level of the area was high with NDVI reaching 0.7-0.8. The similar improvements also detected on the south side of the study area (Figure 2).

The condition in Teluk Pangpang is in contrasts with the majority of mangrove forests on Java Island, particularly those located in urban areas that experience significant decrease in area, for example in Semarang and Jakarta (Aulia et al. 2015; Mulyaningsih et al. 2017), with the exception of Surabaya, which has grown significantly in size in the last ten years (Hidayah et al. 2022). Mangrove areas, particularly in major cities, are vulnerable to settlement expansion, industrial development, and land clearing for fish ponds. Teluk Pangpang's designation as an EEA, which functions similarly to conservation areas, directly prevents land conversion and illegal logging. This policy leaves the area relatively unaltered, allowing natural processes that promote mangrove growth to continue in a safe environment (Hidayati et al. 2020). Moreover, the growth of mangrove vegetation in the area protects the coastline while also maintaining ecological balance, which includes the hydrological cycle, improved air quality, and the protection of various animal and plant species (Sari et al. 2019). The existence of nature conservation areas improves the aesthetic value of the landscape by providing a space for recreation, experimentation and education (Spalding and Parrett 2019).

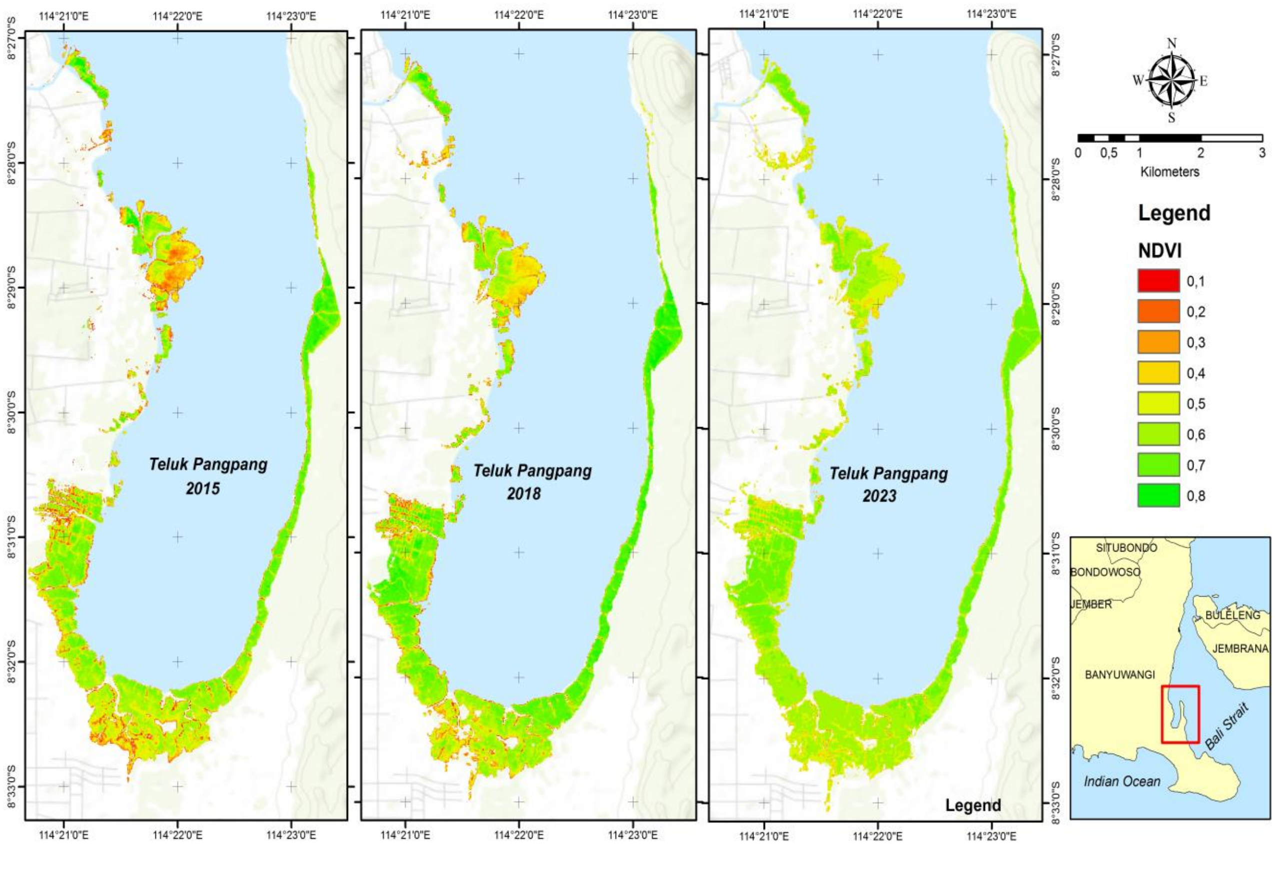


Figure 2. Mangrove extent in Teluk Pangpang, Banyuwangi District, East Java Province, Indonesia, showing a significance increase from 645.35 ha in 2015 to 737.51 ha in 2023 with average growth of ±11.52 ha/year

Mangrove community structure

A series of field survey conducted between September and November 2023 identified seven mangrove species from five families, including *Rhizophora apiculata* Blume, *R. mucronata* Lam., *Bruguiera gymnorrhiza* (L.) Lam. (Fam. Rhizophoraceae), *Sonneratia alba* (Fam. Lythraceae), *Avicennia marina* (Forssk.) Vierh., *Acanthus ilicifolius* L. (Fam. Acanthaceae) and *Xylocarpus moluccensis* (Lam.) M.Roem. (Fam Meliaceae). The finding of this study on mangrove species differ from previous research in 2017 (Rodiana et al. 2019), which found a higher number of mangrove species with additional two species, namely *R. stylosa* Griffith and *Ceriops tagal* (Perr.) C.B.Rob. This difference is most likely due to variations in transect placement. According to the IUCN Red List of Threatened Species 2019, all species of mangroves found in Teluk Pangpang recorded in this study are listed as Least Concerned (LC). Furthermore, *R. apiculata* and *R. mucronata* were the most abundant species which were found almost at all transects/stations. Meanwhile, the species *A. ilicifolius* and *X. moluccensis* were only found in three or four transects. The distribution of mangrove species found accross all obervation transect is presented in Table 3.

According to species distribution, mangrove forest in Teluk Pangpang form a fairly clear zoning. The *R. apiculata*, *R. mucronata,* and *S. alba* dominate the outer zone facing the sea in the bay's western part. The mangrove vegetation at this point is the result of rehabilitation program conducted by the East Java Provincial government between 2000 and 2003. Whereas in the middle zone, located in the inner part of the bay, more species are present, including *A. marina*, *B. gymnorrhiza* as well as *A. ilicifolius* and *X. moluccensis*, although in small numbers. This middle zone is a natural mangrove ecosystem and has the thickest forest in the bay, allowing different types of mangroves to grow. Meanwhile, the eastern part of the bay is part of Alas Purwo National Park and covered in relatively thin mangrove forests dominated by *R. apiculata* and *A. marina*.

The extensive distribution of the genus *Rhizophora*, *Avicennia*, and *Sonneratia* in Teluk Pangpang is consistent with the findings of Giesen et al. (2007) and Tomlinson (2016), which stated that these three mangroves genera are the primary vegetation communities that compose mangrove ecosystem, particularly in the Indo-Pacific coastal region. The genus *Rhizophora* grows in groups near or on tidal riverbeds and at river mouths, and only rarely grows far from tidal waters. Deeply inundated areas, as well as nutrient-rich soils, support optimal growth of this genus. Rhizoporaceae is one of the most important and extensively distributed mangrove family, extending from Indo-West Pacific and Atlantic-East Pacific regions (Takayama et al. 2021). The *S. alba* is commonly found along coastal areas that are protected from waves, alongside estuaries and offshore islands. This species can grow in sediments composed of mud and sand, or on rocks and corals. In addition, *S. alba* can form dense stands in areas where other plant species have been cleared and is mainly distributed in Southeast Asia, Australia, and the Pacific Islands (Saenger et al. 2019). Meanwhile, *A. marina* is a pioneer species on protected coastal land, can occupy and grow in a variety of tidal habitats, particularly saline environments. This species is one of the most common mangrove species found in tidal zones, and forms a group in one particular habitat. The root system of *A. marina* have been reported to help bind sediments and accelerate soil formation. The *A. marina's* global distribution includes Asia, Africa, South America, Australia, Polynesia, and New Zealand (Noor et al. 2007; Saenger et al. 2019).

Further analysis to describe structure of the vegetation community was examined using IVI. This index was calculated based on the number of mangrove stands per species found in the area to determine the level of species importance in a coastal forest community. Field surveys from 15 transects with a total of 75 (10×10 m^2) plots were able to identify a total of 2845 individual mangrove stands. *R. mucronata* and *R. apiculata* were the two most abundant mangrove species in this study and have a significant impact on the overall mangrove ecosystem in Teluk Pangpang. This can be confirmed by the IVI values for the two species, which were 148.24 and 140.91, respectively. Moreover, *S. alba* ranked third with IVI of 125.48, while *A. ilicifolius* was least dominant mangrove species in the area with IVI of 19.65. Table 4 shows the IVI results for mangrove community structure in Teluk Pangpang.

The next analysis was performed to determine the ecological indices of mangrove forest in Teluk Pangpang using three indices (Figure 3). The results show that the community structure of mangroves differ in three zones namely the rehabilitation area, the natural mangrove growth area, and the mangrove area within the Alas Purwo National Park, Indonesia. The rehabilitated mangrove area to the west of the bay is characterized by low species diversity ($0.25<H'<0.6$), high species uniformity ($0.61<J<0.85$) and a high dominance index ($0.79<D<1$). Prior studies have reported that rehabilitated mangrove areas are usually dominated by specific species (Suwanto et al. 2021; Xiong et al. 2021). Further investigation revealed that during the rehabilitation process from 2000 to 2003, available mangrove species with a high survival rate were chosen, specifically the Rhizophoraceae family (Rodiana et al. 2019). This fact could explain the abundance of *R. apiculata* and *R. mucronata* in transects S1-S3. Meanwhile in transects S4 - S13, which were located at naturally grow mangrove forest, showed higher diversity of mangrove species. The Diversity Index (H') in this area ranged between 0.43 and 2.53, indicating medium diversity. Field data confirmed that the area contains almost all of Teluk Pangpang mangrove's species. In contrast, the diversity of mangrove species decreased along transects S14 and S15 ($H'<0.5$), which is the part of the Alas Purwo National Park.

Mangrove ecosystem in Teluk Pangpang has more species compare to several other locations in East Java, for example, in Pasuruan and east coast of Surabaya, which have only five mangrove species. However as presented in Table 5, the natural part of Teluk Pangpang has significantly less mangrove species than the natural mangrove forest ecosystems of Mimika Papua, Indonesia (66 species), Banaybanay Davao, Philippines (33 species) and Setiau Wetland of Trenggganu, Malaysia (20 species) (Pototan et al. 2021; Setyadi et al. 2021; Rahman et al. 2023). Nonetheless, Table 5 also confirms that natural mangrove forests, particularly in Southeast Asia, have a significantly higher diversity of mangrove species compare to mangrove forests situated in rehabilitation area. In a natural habitat, the variation in community structure and species diversity can be affected by geomorphological conditions and biophysical factors (Cameron et al. 2021). Biophysical conditions that support mangrove's growth include high levels of nutrient availability, temperature, sediment supply, freshwater influx and tidal amplitude (Alongi 2012; Cameron et al. 2019; Ochoa-Gomez et al. 2019). The differences in species composition are influenced by geomorphic settings as well as the interaction of biophysical processes that vary along intertidal gradients.

Water quality parameters

Water quality parameters were measured in-situ at all observation stations. Table 6 summarizes the statistical values for the measured water quality parameters. Water salinity in the area ranged from 5.5 to 32°/$_{oo}$, with an average of 21.93±8.96°/$_{oo}$. This wide salinity range was caused by significant difference between stations in the western part adjacent to the estuary of the Kalisetail River (S1-S3) and other transects in the southern and eastern parts of Teluk Pangpang (ANOVA test, $p<0.05$, df = 44). The measured salinity along the S1-S3 stations was much lower, ranging from 6.33°/$_{oo}$ to 8.16°/$_{oo}$, compared to S4-S15 which exceeded 25°/$_{oo}$. The significant difference of salinity was due to the influx of fresh water carried by the Kalisetail River flow.

Table 3. Distribution of mangrove species accross all observation transects in Teluk Pangpang, East Java Province, Indonesia

Species	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
Rhizophora apiculata	●	●	●	●	●	●	-	●	-	●	-	-	●	●	●
Rhizophora mucronata	●	●	●	●	●	●	●	●	●	●	●	●	-	-	-
Bruguiera gymnorrhiza	-	-	-	-	●	●	-	●	●	●	-	●	-	-	-
Avicennia marina	-	-	-	-	-	-	●	●	●	●	●	●	●	●	●
Sonneratia alba	●	●	●	●	●	-	●	●	●	●	-	-	●	-	●
Acanthus ilicifolius	-	-	-	-	-	-	●	-	●	●	●	-	-	-	-
Xylocarpus moluccensis	-	-	-	-	-	-	-	●	●	●	●	-	-	-	-

Notes: (●) present; (-) absent

Table 4. Community structure of mangrove vegetation in Teluk Pangpang, Banyuwangi District, East Java Province, Indonesia

Family	Mangrove species	Estimated Mean Density (Ind/ha)	Relative Density (RDi)	Relative Frequency (RFi)	Relative Coverage (RCi)	IVI
Acanthaceae	*Avicennia marina*	1431±215	29.36	25.78	29.70	84.79
	Acanthus ilicifolius	611±72	2.16	12.50	4.99	19.65
Rhizophoraceae	*Rhizophora apiculata*	2300±145	46.98	47.33	46.60	140.91
	Rhizophora mucronata	2875± 200	43.11	33.98	71.15	148.24
	Bruguiera gymnorrhiza	1725±130	28.13	16.25	42.37	86.75
Lythraceae	*Sonneratia alba*	1924± 125	60.38	47.97	17.13	125.48
Meliaceae	*Xylocarpus moluccensis*	1057±170	16.47	25.00	10.87	52.34

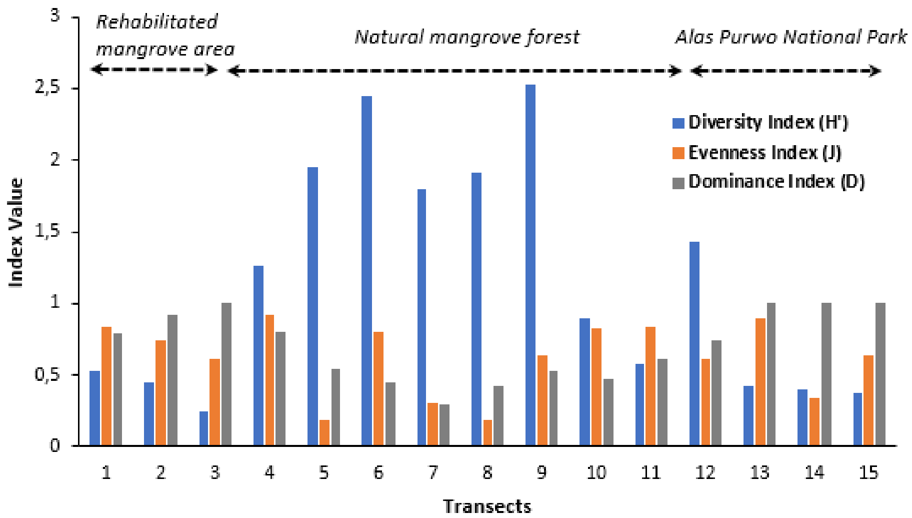


Figure 3. Ecological indices of mangrove vegetation in Teluk Pangpang, Indonesia based on diversity, evenness and dominance

Table 5. Comparison of mangrove species diversity between the present study and other studies

Locations	No of species	Diversity (H')	Dominant species	Source
Teluk Pangpang, East Java (the natural part)	7	2.5	*Rhizophora mucronata*	*Present study* (2024)
Blanakan Subang, West Java**	6	1.32	*Avicennia marina*	Suwanto et al. 2021
Moramo Bay, South East Sulawesi*	7	0.35	*Rhizophora mucronata*	Oetama et al. 2023
Indramayu, West Java**	6	0.95	*Rhizophora mucronata*	Gunawan et al. 2017
Mimika, Papua*	66	1.19	*Rhizophora apiculata*	Setyadi et al. 2021
Baluran National Park, East Java**	8	1.31	*Rhizophora stylosa*	Asadi and Pambudi 2020
Banaybanay Davao, Philippines*	33	3.14	*Sonneratia alba*	Pototan et al. 2021
Setiu Wetland, Malaysia*	20	1.05	*Rhizophora mucronata*	Rahman et al. 2023
Barangay Cagdianao, Philippines**	9	1.54	*Lumnitzera racemosa*	Goloran et al. 2020
Merlimau Reserve Jasin Malaka, Malaysia**	9	0.56	*Avicennia marina*	Azman et al. 2021
Bach Dang Estuary, Vietnam*	22	2.90	*Excoecaria agallocha*	Vu et al. 2022

Note: *Natural mangrove forest; **Rehabilitated mangrove forest

Table 6. The statistics of water quality parameters measurement in Teluk Pangpang Mangrove Forest, East Java Province, Indonesia

Water quality parameters	Maximum	Minimum	Range	Mean±SD	SE
Salinity (‰)	32	5.5	26.5	21.93± 8.96	1.33
Temperature (ºC)	35	27	8	30.91± 2.10	0.34
pH	8.5	6	2.5	7.25± 0.58	0.08
DO (mg/L)	6.5	4.3	2.2	5.09±0.89	0.13
TSS (mg/L)	75	15	60	36.88±15.64	2.33

Table 7. The extent and proportion of mangrove forest condition between 2015 and 2023 in Teluk Pangpang, East Java Province, Indonesia, based on MHI analysis

Year	Total area of mangrove forest based on MHI categories					
	Poor		Moderate		Excellent	
	Area (ha)	%	Area (ha)	%	Area (ha)	%
2015	552.23	85.56	82.13	12.72	11.00	1.70
2018	408.34	60.01	196.74	28.91	75.36	11.07
2023	339.39	46.01	226.26	30.13	175.86	23.84

The TSS measurement results in this study were also influenced by differences in observation's location. The average TSS concentration measured in Teluk Pangpang was approximately 36.88±15.64 mg/L, with a wide range of up to 60 mg/L. Significant TSS differences were observed between stations at the Kalisetail River estuary (S1-S3) and other locations (S4-S15). TSS concentration at S1-S3 ranged between 56.67 mg/L to 65.55 mg/L. This TSS range was significantly higher than the average TSS concentration at other stations, which ranged from 20.00 mg/L to 37.50 mg/L (ANOVA test, $p<0.05$, df = 44). The high concentration of TSS in S1-S3 stations was caused by solids accumulated as a result of soil and sediment erosion by water flows that are carried and deposited at the estuary area.

Meanwhile, measurements of other parameters including temperature, pH, and DO appeared not to vary significantly among observation stations (ANOVA test, $p>0.05$, df = 44). The average temperature measured was 30.91±2.10 ºC, with a stable pH of 7.25±0.58. In addition, DO measurement results were consistent across all stations, with an average of 5.09±0.89 mg/L. In general, all water quality parameter values in Teluk Pangpang mangrove ecosystem remain within the water environment standards for marine biota as specified by the Indonesia Ministry of Environment and Forestry No 22/2022.

Spatio-temporal dynamics of Mangrove Health Index (MHI)

MHI spatial analysis was performed using a combination of four vegetation indices derived from the equation developed by Nurdiansah and Dharmawan (2021). The similar calculation formula was used in other studies, such as Dharmawan (2021) and Sugiana et al. (2022). The result of analysis showed that the overall condition of mangrove forest in Teluk Pangpang improved between 2015 and 2023, as measured by the MHI value. The result of MHI analysis is shown in Figure 4.

The spatial distribution of MHI in Teluk Pangpang varied from 2015 to 2023. The MHI analysis in 2015 showed that the majority of the mangrove area in Teluk Pangpang, approximately 85.56% (552.23 ha) was in poor condition. Meanwhile, the remaining area around 93.13 ha, was in a moderate to excellent MHI state. Afterwards, according to the 2018 results, the area of mangroves with moderate to excellent MHI conditions increased to 196.74 ha and 75.36 ha, respectively. Furthermore, the condition of mangroves improved significantly in 2023. Over that period, the moderate MHI category comprised 226.16 ha of the total area, while the excellent MHI category covered increased to 175.86 ha. When compared to previous condition in 2018, the area of mangrove forests in poor condition decreased by 17.05%, or more than 68 ha. Finally, by 2023, the proportion of mangrove forest area in moderate to excellent MHI condition was 53.98% of the total mangrove forest area or approximately 737.51 ha (Table 7).

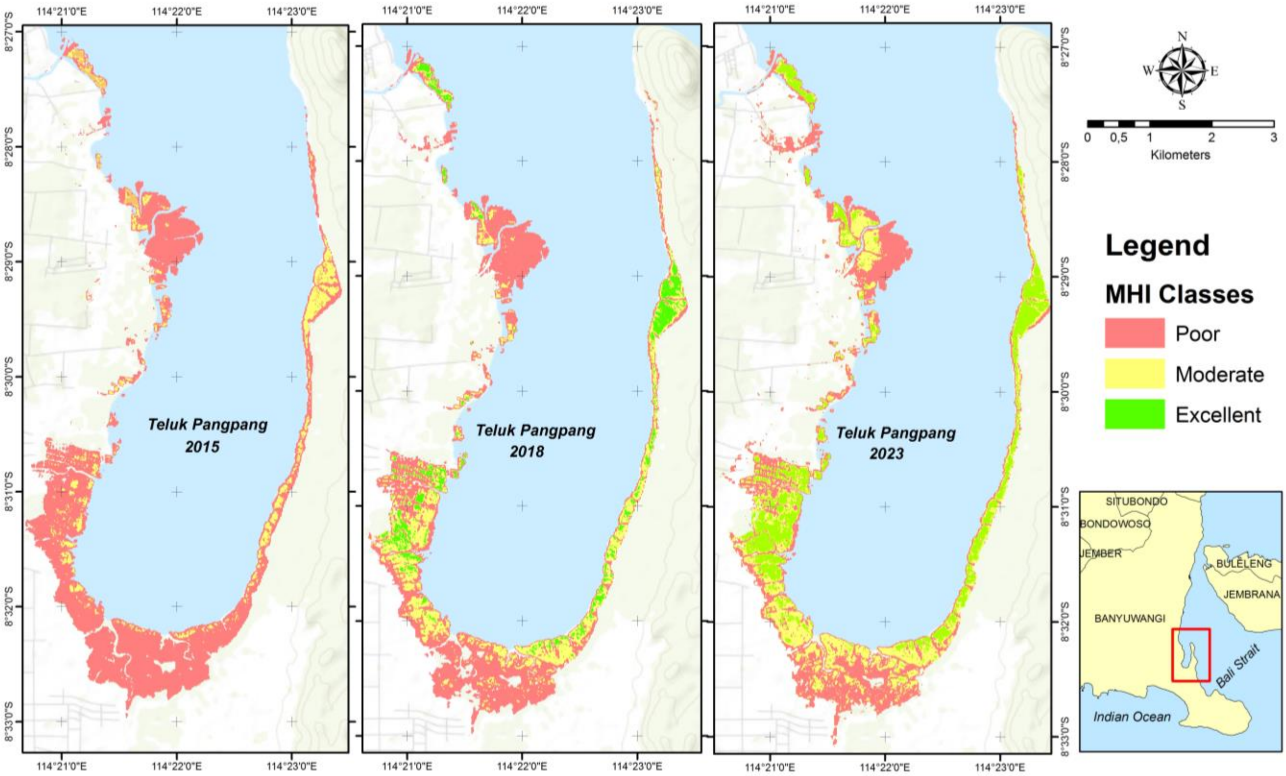


Figure 4. Spatio-temporal dynamics of MHI of Teluk Pangpang Mangrove Forest, East Java Province, Indonesia, based on a combination of four vegetation indices Normalized Burn Rasio (NBR); Green Chlorophyll Index (GCI); Structure Insensitive Pigment Index (SIPI) and Atmospherically Resistant Vegetation Index (ARVI) derived from Sentinel-2 images

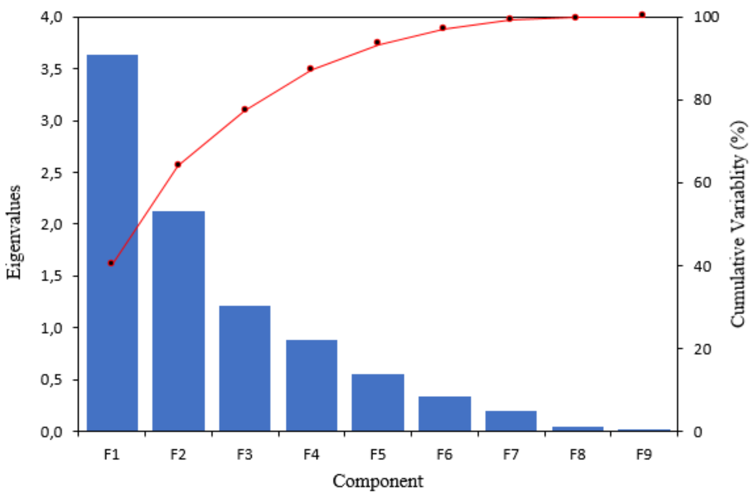
Principal Component Analysis (PCA)

Satellite imagery may represent the most effective way to determine the spatial distribution of MHI, particularly to investigate temporal changes. However, limitations in the use of satellite imagery must be considered. Satellite sensors cannot detect water or sediment conditions under the canopy, which have a significant impact on environmental quality and mangrove vegetation growth. Therefore, in this study we used PCA, a multivariate analysis to examine the characteristic of all observation transects based on MHI from image processing and actual environmental condition determined through field observation. Applying PCA may provide more insight into the relationship between MHI, ecological indexes, and water quality parameters of Teluk Pangpang Mangrove Forest.

The PCA results are presented with a scree plot (Figure 5), demonstrating that grouping observation stations of Teluk Pangpang Mangrove Forest based on nine environmental characteristics can be accomplished using three factors, namely PC_1, PC_2, and PC_3. These three factors account for 77.36% of the total variation and is considered to represent the total diversity of existing data because it ranges between 70% and 80% (Jalil et al. 2020; Marpaung et al. 2022). Variables with a factor loading value of $\geq$0.5 are acceptable for further analysis, with the goal of obtaining significant variable values (Hair et al. 2020). Further analysis showed that salinity, DO, TSS, mangrove's species diversity, and MHI are the parameters that significantly influence station grouping in PC_1, which has an eigenvalue of 40.34%. Station grouping in PC_2 with eigenvakue of 23.56% is mainly influenced by salinity, pH, DO and mangrove's domination index. Meanwhile, in PC3 (eigenvalue 13.44%), the only influencing parameter is mangrove's evenness index.

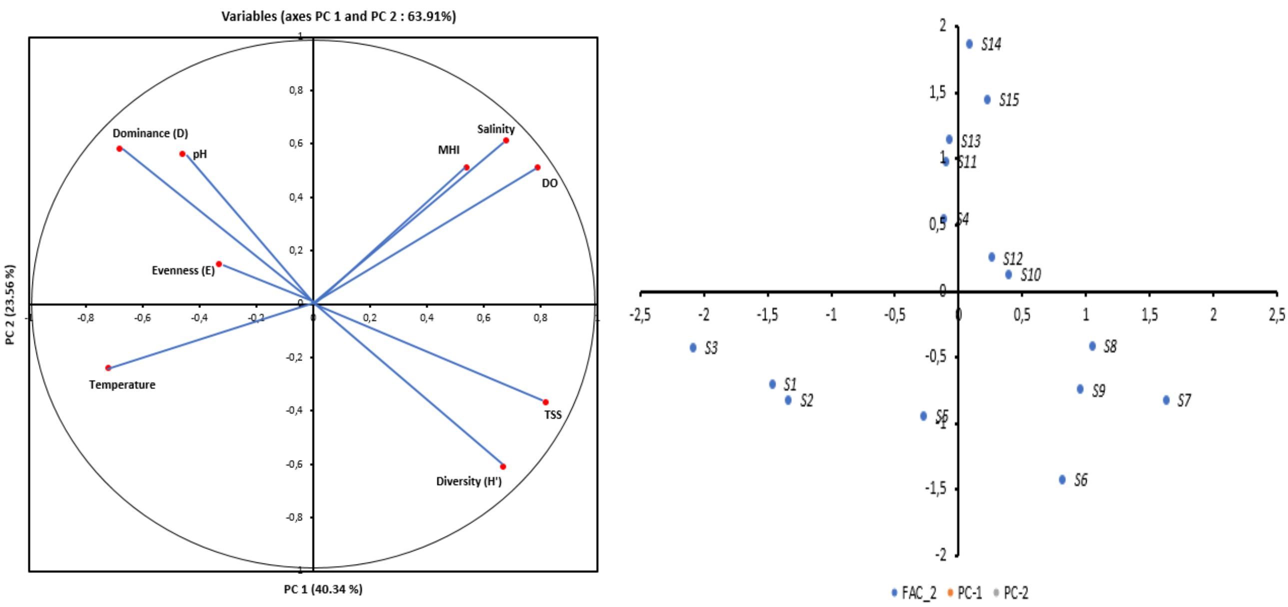
Furthermore, the PCA results in Figure 6.A explain the magnitude and correlation of parameters that influence the mangrove environment in Teluk Pangpang. Longer PCA lines indicate a greater role for character in grouping, whereas the angle formed by each line for each variable indicates the degree of correlation between variables. Specifically, the PCA findings in Teluk Pangpang suggest that the distribution of mangrove forest conditions based on MHI is strongly correlated with salinity, DO, TSS, and mangrove's diversity index (PCA, Pearson correlation, $p<0.05$). In contrast, other variables less related to MHI in this study include pH, temperature, mangrove's dominance and evenness index. The next PCA result is a grouping of stations based on environmental characteristics, as shown in Figure 6.B. The stations characterized by high MHI, salinity, and DO values are S4 and S10-S15. Meanwhile, stations S6-S9 are characterized by diversity index and TSS, on the other hand temperature appears to affect S1-S3.

MHI analysis is an alternative approach for assessing the condition of mangrove forests. Other studies have determined field-based MHI by calculating tree density, canopy cover percentage, mangrove diversity, seedling presence, and other supporting data. MHI calculations using field surveys had been performed in several location for instance Karimun Jawa National Park and Bunaken mangrove forest of North Sulawesi, Indonesia (Prasetya et al. 2017; Schaduw et al. 2021). Meanwhile, the use of satellite imagery to determine MHI spatial distribution is limited in a number of locations, including Biak Island of Papua and Benoa Bay, Bali (Dharmawan 2021; Sugiana et al. 2022). The health of mangrove of Teluk Pangpang has improved along with a significant increase in mangrove's area. The similar condition was also experienced by Biak Island's mangrove forests, which have been reported to have improved conditions based on MHI analysis. Mangrove areas with moderate and excellent MHI categories increased at this location over two observation periods from 2015 to 2020. Within that period, the area in moderate status increased by 27.07 ha, from 175.71 ha to 202.78 ha. Likewise, the area of the excellent mangrove category increased substantially from 24.53 ha to 64.16 ha during the observation period (Dharmawan 2021). In Benoa Bay Bali, it was also reported that mangrove health is improving considerably (Sugiana et al. 2022). Based on the MHI spatial distribution area in 2021, the majority of Benoa Bay mangroves around 564.96 ha were classified as in excellent condition. Meanwhile, the moderate and poor categories accounted for approximately 40.76% and 11.51% of the bay's total mangrove area, respectively.



Parameters	Components		
	PC 1	PC 2	PC3
Salinity	**0.683**	**0.607**	0.119
Temperature	-0.724	-0.239	0.357
pH	-0.455	**0.562**	0.197
DO	**0.791**	**0.505**	0.115
TSS	**0.818**	-0.365	-0.073
Diversity	**0.673**	-0.611	0.016
Evenness	-0.330	0.154	**0.857**
Dominance	-0.680	**0.579**	-0.070
MHI	**0.540**	0.207	-0.521

Figure 5. The results of PCA showing total variance explained by eigenvalues (scree plot) and components matrix (loading factors) of PC_1, PC_2 and PC_3



A B

Figure 6. A. Correlation plot between variables; B. Station grouping based on PC_1 and PC_2

The poor MHI condition can be explained at least by two factors, namely the natural occurrence of dieback and the condition of vegetation in the growth stage. Mangrove's dieback phenomenon is characterized by a decrease in the percentage of canopy cover caused by the fall of a massive amount of mangrove leaves. Changes in salinity are the primary cause of mangrove dieback because they control cellular osmotic pressure. Higher salinity levels could reduce mangrove biomass growth, increase osmotic pressure, and reduce leaf area (Rosas et al. 2023). Further investigation of chemical compositions in mangrove stems and sediments reveals that excessive Fe element absorption by mangroves is also a cause of dieback (Sippo et al. 2018). Moreover, low water availability during a strong El Niño-Southern Oscillation (ENSO) event and climate change have been linked to massive mangrove dieback in Australia, according to multiple reports in 2016 to 2020 (Duke et al. 2021; Hickey et al. 2021; Chung et al. 2023). As observed from space, the canopy cover has a significant influence on the determination of the MHI category using satellite images. Due to the low canopy cover, the area of rehabilitation that has recently planted vegetation is classified as in poor state. This seems to have occurred during this study, particularly in the west side of Teluk Pangpang mangrove area adjacent to the Kalisetail estuary.

This study performed in Teluk Pangpang suggests that the area of MHI in the moderate to excellent category is gradually increasing. One indicator that can be seen to support this finding is the increased density of mangrove vegetation, as evidenced by higher NDVI value. It also confirms that the expansion of mangrove forests in Teluk Pangpang is accompanied by healthy development and growth of mangrove vegetation. The increasing state is also due to the absence of illegal logging, pollution, land conversion and coastal reclamation that allows mangroves to grow in their natural habitat. Moreover, this study suggests that further MHI applications include using the analysis results as important information in the management and protection of mangrove conservation areas. This analysis identifies the distribution of potential rehabilitation points, which can then be improved by planting mangrove seedlings. Spatial monitoring with MHI allows managers of mangrove conservation areas to formulate improvement scenarios at predetermined locations which is obviously useful in assessing the success of the mangrove rehabilitation program.

In conclusion, this study has demonstrated the use of GIS analysis and remote sensing technology to map the spatio-temporal dynamics in mangrove ecosystem conditions in Teluk Pangpang, Banyuwangi District, East Java Province. Sentinel-2 satellite image processing successfully identified a significant increase in mangrove's area, from 643.35 ha in 2015 to 737.51 ha in 2023. Over the same time period, mangrove vegetation density increased from 0.45±0.08 to 0.67±0.09 based on average NDVI pixel values. The most dominant mangrove species found in the area were *R. mucronata* and *R. apiculata*, with IVI values of 148.24 and 140.91, respectively. In addition, MHI calculations also clearly indicated improving conditions, as evidenced by the substantial increased area of mangroves in the excellent MHI category (MHI>66.8) from 11.00 ha in 2015 to 175.86 ha in 2023. Furthermore, the spatial distribution of MHI in Teluk Pangpang was significantly correlated to several water quality parameters and community structure indicators, including salinity, DO, TSS, and mangrove's diversity index.

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