INDO PAC J OCEAN LIFE
Volume 8, Number 2, December 2024
Pages: 101-111

P-ISSN: 2775-1961
E-ISSN: 2775-1953
DOI: 10.13057/oceanlife/o080205

Mangrove dynamics on the Madura Island coast, Indonesia, analyzed through NDVI: Balancing degradation and restoration efforts

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Manuscript received: 25 November 2024. Revision accepted: 30 December 2024.

Abstract. *Ramadhani G, Wahyuningtyas J, Arifiandita DM, Ayuningtyas HR, Deristani A, Ulumuddin YI, Setyawan AD. 2024. Mangrove dynamics on the Madura Island coast, Indonesia, analyzed through NDVI: Balancing degradation and restoration efforts. Indo Pac J Ocean Life 8: 101-111.* Mangrove ecosystems are plant communities that thrive at the interface between land and sea, but they face significant threats, particularly from land conversion. The mangrove forests along the coast of Madura have experienced a decline in coverage due to such conversion. This study offers valuable insights into changes in mangrove areas and uses NDVI analysis to assess these changes from 2019 to 2024. The study focuses on monitoring mangrove forest distribution and changes in the Bangkalan, Sampang, Pamekasan, and Sumenep coastal areas. Primary data were obtained from Sentinel-2A - 2A satellite imagery of Madura. Data analysis used the Kappa Analysis method to validate mangrove density classification. Results showed an increase in mangrove coverage in Bangkalan between 2019 and 2024, with the moderately dense category rising from 348.9 to 355.3 hectares and the dense category increasing from 114.7 to 150.1 hectares. Similarly, in Pamekasan, the moderately dense classification grew from 305.4 to 409.3 hectares. However, overall, the reduction in mangrove forest area was more significant than the increase. The Kappa accuracy of 70% indicated moderate reliability, with data discrepancies in 14 out of 40 points. In Madura's mangrove forests, conservation efforts include education, conservation initiatives, and community empowerment through sustainable environmental communication strategies.

Keywords: Density, health, kappa coefficient, mangrove, NDVI

INTRODUCTION

Mangrove ecosystems are plant communities that thrive between sea and land, are influenced by tidal movements, and are commonly found in shallow bays, estuaries, and deltas (Rizqi et al. 2023). Their adaptive root systems protect coastlines from erosion and tsunamis (Shiau et al. 2020). However, mangroves are threatened by human activities, including urbanization and industrial expansion (Hidayah et al. 2015). As the country with the most extensive mangrove coverage, Indonesia must prioritize sustainable management and conservation of these essential ecosystems (Sidik et al. 2018).

According to data from the Geospatial Information Agency (GIS), Indonesia's mangrove forests covered 3.36 million hectares in 2017 (Rahadian et al. 2019). In Madura, mangroves extend over 12,115.8 hectares, distributed across several areas: Bangkalan (1,508.1 hectares, 10%), Sampang (915.3 hectares, 6.1%), Pamekasan (599.3 hectares, 4%), and Sumenep, including its islands (12,095.4 hectares, 80%) (Muhsoni et al. 2019). The protection of mangrove forests involves monitoring through remote sensing and GIS technologies, which utilize satellite imagery for accurate mapping (Giri et al. 2021). Due to their location between land and sea, mangroves exhibit unique spectral characteristics that necessitate specific transformations of vegetation indices for effective detection (Kawamuna et al. 2017).

In 2017, Indonesia's mangrove forests covered 3.36 million hectares (Rahadian et al. 2019), with Madura accounting for 12,115.8 hectares: Bangkalan (10%), Sampang (6.1%), Pamekasan (4%), and Sumenep (80%) (Muhsoni et al. 2019). Mangrove protection can be improved using remote sensing and GIS, which leverage satellite imagery for precise mapping (Giri et al. 2021). Due to their transitional location between land and sea, mangroves require specific spectral transformations, often using vegetation index techniques, for accurate detection (Kawamuna et al. 2017).

Mangrove ecosystems are evaluated based on species diversity, density, canopy cover, and biomass (Schaduw et al. 2019). In Indonesia, over 70% of mangroves are damaged due to human activities. Madura's mangroves span 15,118.2 hectares, with 8,794.1 hectares in good condition and 6,324.1 hectares degraded (Hidayah et al. 2024). Logging, land conversion, and waste disposal have significantly reduced mangrove coverage and health, especially along Madura's coast (Hidayah 2015; Rosyid et al. 2021).

Satellite imagery allows for the analysis of mangrove ecosystems using vegetation indices such as NDVI, which is known for its accuracy and correlation with vegetation density (Razali et al. 2019). The Mangrove Health Index (MHI) evaluates ecosystem health based on parameters like stem diameter, canopy cover, and density using field data or satellite imagery (Hidayah et al. 2023). Research by Nurdiansyah et al. (2021) demonstrates a strong correlation between these parameters and vegetation indices, which can be derived from satellite image analysis. MHI values can be predicted using several vegetation indices, including NBR (Normalized Burn Ratio), GCI (Green Chlorophyll Index), SIPI (Structure Insensitive Pigment Index), and ARVI (Atmospherically Resistant Vegetation Index).

Mangrove density has a close relationship with the dynamics of mangrove area change from 2019 to 2024 on the south coast of Madura. Increases in mangrove density often reflect successful natural regeneration or successful rehabilitation programs, such as mangrove planting in previously degraded areas. Conversely, a decrease in mangrove area can occur due to the pressure of human activities, such as land conversion to salt ponds, as well as the impacts of coastal abrasion and climate change. The aims NDVI analysis shows that changes in mangrove area in the period 2019-2024 with increasing pressure on mangrove land on the south coast of Madura, sustainable management efforts are needed to maintain a balance between optimal mangrove density and the sustainability of its area to support the coastal ecosystem as a whole.

MATERIALS AND METHODS

Study area

This study monitors the distribution and changes in mangrove forest coverage along the coast of Madura Island, specifically focusing on mangrove dynamics from Bangkalan to Sumenep (Figure 1). Located near the equator, Madura Island is one of the driest regions in Indonesia, characterized by high temperatures and low humidity levels (Wasonowati et al. 2019). Temperatures along the Madura coast range from 23 to 31°C year-round; humidity in the coastal areas varies between 42 and 92%, depending on rainfall and other factors. The average annual rainfall on Madura Island ranges from 1,328 to 1,571 mm, with December typically experiencing the highest rainfall, averaging up to 275 mm (Agustin and Syah 2020).

Factors influencing the weather on the coast of Madura Island include flat topography, monsoon wind speed and direction, mangrove conditions, sea surface temperatures, human activities, and other atmospheric and oceanographic factors. Each mangrove species has varying tolerance to salinity. For example, *Avicennia* spp. can tolerate salinity levels up to 85 ppm, while *Bruguiera gymnorhiza* thrives in areas with salinity levels between 10 and 37 ppm (Natarajan et al. 2021). Most mangrove plants achieve their highest leaf production rates at temperatures between 26 and 28°C and pH levels of 8 to 9 (Martínez-Díaz and Reef 2023).

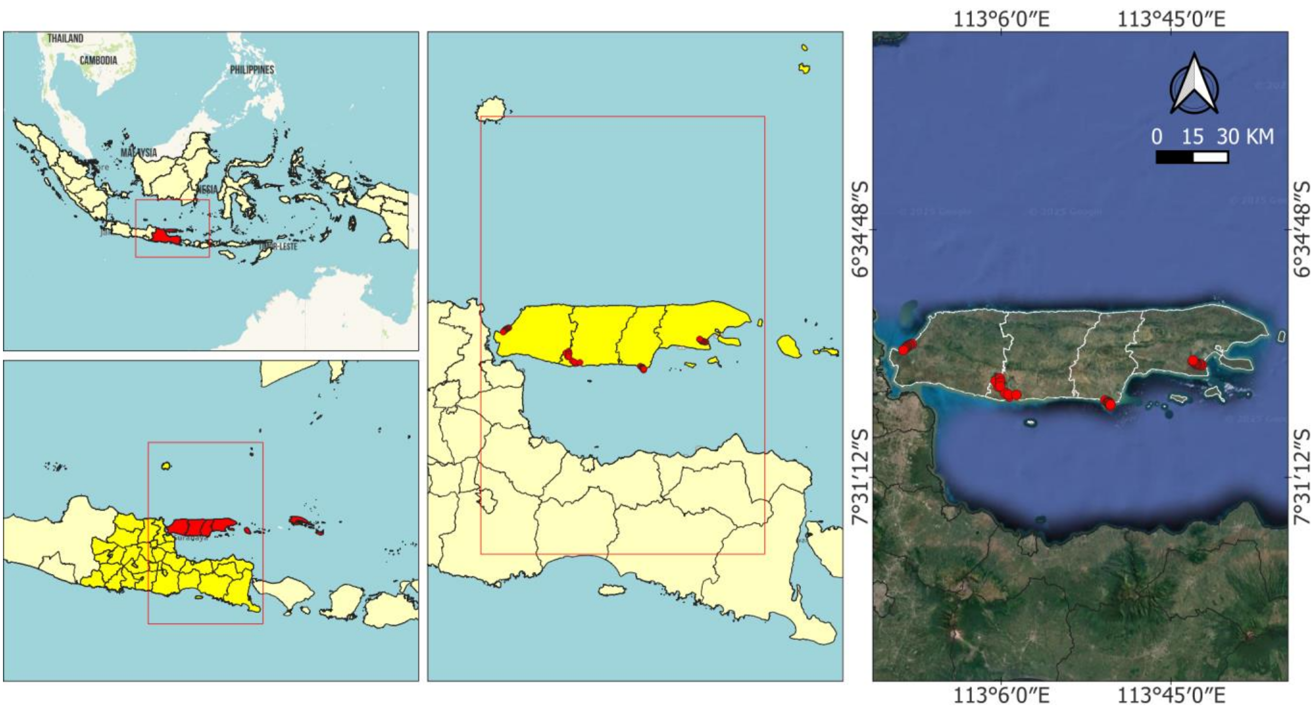

Figure 1. The study Area on the coast of Madura Island, East Java Province, Indonesia, includes 4 districts, i.e.: Bangkalan, Sampang, Pamekasan, and Sumenep

The study area for mangrove forest coverage on the coast of Madura Island (Figure 1) includes Bangkalan District (112°40'06"-113°08'04" E and 6°51'39"-7°11'39" S), Sampang District (113°08'-113°39' E and 6°05'-7°13' S), Pamekasan District (113°19'-113°58' E and 6°51'-7°31' S), and Sumenep District (113º32'-116º16' E and 4º55'-7º24' S). The coast of Madura Island experiences stronger abrasion and accretion currents compared to the northern coast, with higher levels of human activity. In 2023, Madura Island had a population of approximately 4.1 million people, with 905,151 residents in Bangkalan District and 1,042,276 in Sumenep District (BPS East Java Province 2023). Land use on Madura includes settlements, rice fields, farms, dry land, salt ponds, and mangrove forests (Hidayah and Suharyo 2018). The mangrove species commonly found in the area include Avicenniaceae, *Rhizophora*, *Avicennia marina*, *Bruguiera gymnorhiza*, *Acanthus ilicifolius*, and others (Rosadi et al. 2018).

Procedures

Types and sources of data

The primary data used in this study are Sentinel-2A imagery, selected for analyzing mangrove density along the coast of Madura Island in 2019 and 2024. Sentinel-2A imagery was obtained from the USGS Earth Explorer data portal. Sentinel-2 imagery is commonly used for monitoring spatial dynamics, especially in mangrove areas (Wang et al. 2018). Secondary data include administrative maps of Madura Island, QuickBird maps (Google Earth), and relevant literature reviews. The administrative maps were obtained from the Geospatial Information Agency (Badan Informasi Geospasial, BIG) of Indonesia

Processing method

The processing method involved transforming Sentinel-2A imagery of the Madura coastline using band combinations to create vegetation indices. The index used in this study is the NDVI (Normalized Difference Vegetation Index). The principle of NDVI is to measure the level of greenness intensity using the following formula (Naharudin 2021):

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$$

Where:
NIR: Near Infrared (Band 8)
Red: Red Band (Band 4)

Near Infrared (Band 8) and Red Band (Band 4) are bands sensitive to the chlorophyll content in plant leaves, which serves as an indicator of vegetation distribution (Zhen et al. 2021). The formula can indicate NDVI values for the target area. According to Hanif (2015), NDVI values range between -1.0 and 1.0. Based on vegetation density, NDVI values are classified into four categories: water/cloud, non-vegetation, sparse, moderately dense, and dense (Table 1). This research utilizes ArcGIS 10.8 software to generate NDVI maps through spatial analysis.

Table 1. NDVI value classification

Vegetation density classification	NDVI Value
Cloud and water	-2 - 0
Non vegetation	0 - 0.2
Low dense	0.2 - 0.4
Moderate	0.4 - 0.6
Dense	0.6 - 0.8

Source: Hardianto et al. 2021

Validation

For validation, random sample points were generated on the mangrove area map along the coastline of Madura Island. A total of 40 sample points were selected: 10 along the Sumenep coast, 10 along the Bangkalan coast, 10 along the Pamekasan coast, and 10 along the Sampang coast. These points were selected based on the presence of mangroves, ease of access to data, and the inclusion of all four regencies on Madura Island to ensure comprehensive coverage. The classification results for each point were then compared with NDVI values using QuickBird map imagery from Google Earth. Validation was performed visually by interpreting the predetermined sample points with QuickBird imagery on Google Earth.

Data analysis

Kappa analysis was performed to validate the classification of mangrove density by comparing the classification results from processed image data with field observation data using a confusion matrix (Sari et al. 2022). The confusion matrix (Table 2) serves as a tool to measure data accuracy through simple cross-tabulation. This process involves assessing the agreement between image-processed data and field observation data, providing a basis for evaluating data accuracy. The matrix includes mangrove density classes derived from image classification in its rows and density classes based on field observations in its columns, with the matrix contents representing the number of objects.

The more objects that match the classes in the rows and columns, the higher the accuracy of the mangrove health classification results (Mappiasse et al. 2022). The accuracy of the image classification results is calculated using the overall accuracy, producer's accuracy, and user's accuracy (Vu et al. 2022). The overall accuracy shows the percentage of correctly classified findings based on the observation data with the following formula:

$$overall\ accurancy: \frac{XKK}{N} \times 100\%$$

Where:
XKK: number of observation points that match
N : total number of observation points

Table 2. Matrix of classification density results agreement with field observations

Mangrove density analysis	Field observation data: Cloud and water	Non vegetation	Low dense	Moderate	Dense	Total	Producer's accuracy
Cloud and water	XAA	XAB	XAC	XAD	XAE	∑EC	XAA/∑AC x 100%
Non vegetation	XBA	XBB	XBC	XBD	XBE	∑BC	XBB/∑BC x 100%
Low dense	XCA	XCB	XCC	XCD	XCE	∑CC	XCC/∑CC x 100%
Moderate	XDA	XDB	XDC	XDD	XDE	∑DC	XDD/∑DC x 100%
Dense	XEA	XEB	XEC	XED	XEE	∑EC	XEE/∑EC x 100%
Total	∑AR	∑BR	∑CR	∑DR	∑ER	N	
Producer's accuracy	XAA/∑AR x 100%	XBB/∑BRx 100%	XCC/∑CRx 100%	XDD/∑DRx 100%	XEE/∑ERx 100%	XKK	

Note: ■: Suitable, □: Unsuitable; Source: Abimanyu et al. (2019)

It is known that the total number of sample points obtained is 40, which are randomly distributed, with each district having 10 sample points. These points were selected to obtain the overall accuracy, with the aim of measuring the user's accuracy and the producer's accuracy. The mangrove density classification results can be accepted if the overall classification result reaches >85% (Wicaksono and Wicaksono 2018).

RESULTS AND DISCUSSION

Results

The coastal area of Madura, vulnerable to exploitation, faces increasing pressure from the economic needs of local communities dependent on land use for salt production and aquaculture. The mangrove forest area along the Madura Strait Coast in Sumenep, Pamekasan, Sampang, Bangkalan, Gresik, Surabaya, Sidoharjo, Mojokerto, Pasuruan, Probolinggo, Situbondo, until Bondowoso has decreased by 111.82 hectares (Hidayat and Suharyo 2018). As a result, mangrove coverage shrinks, disrupting its ecological functions and increasing the risk of environmental disasters such as abrasion and seawater intrusion. The decline in NDVI values of mangroves in this region not only impacts the local environment but also undermines the resilience of coastal ecosystems on a regional scale.

The NDVI map of the Bangkalan Coast, derived from Sentinel-2A imagery, is shown in Figure 2. The map highlights areas with high mangrove density along the western coast and a small section on the southeastern side. Different colors represent varying NDVI values. The density of other vegetation types, including shrubs, yard plants, and rice fields, can also be observed in the area. In 2019, the western coast of Bangkalan exhibited dense mangroves, with NDVI values ranging from 0.3 to 0.8, indicating a healthy mangrove population. Mangrove density refers to the concentration of mangrove trees along Madura's coastal areas. Madura's mangroves cover approximately 15,118 hectares across four main districts: Bangkalan, Sampang, Pamekasan, and Sumenep. Mangrove density is measured using satellite imagery methods, such as Landsat 8, which analyzes the Normalized Difference Vegetation Index (NDVI). This data is then compared with field observations to assess the condition and distribution of mangroves. A slight protrusion in the middle of the Bangkalan Coast, observed in both 2019 and 2024, suggests low mangrove density. This is likely due to the presence of built-up areas.

The distribution of mangroves was very dense along the Sampang coast and rivers in 2019 but decreased to dense mangroves in 2024 (Figure 3). This decline may be attributed to anthropogenic activities that have impacted mangrove density in the Sampang Coast area. The dominant density classes in the Sampang coastal region are very low and low density. Very dense mangrove was found along the coastal river channels of Sampang. Compared to the regencies of Bangkalan, Sumenep, and Pamekasan, Sampang experienced a reduction of 210.08 hectares in mangrove forest area (Hidayat and Suharyo 2018).

In 2019, very dense mangroves were identified along the Pamekasan coast, but by 2024, their density had decreased to a dense classification (Figure 4). This change may be caused by anthropogenic activities that could affect mangrove density in the Pamekasan Coast area. Looking at the dominant density classes in the Pamekasan area, there are three density classes: very dense, dense, and moderate. Very dense vegetation was identified along the Pamekasan coast.

In 2019, very dense mangroves were identified in the central area of Sumenep, but by 2024, their density had decreased to a dense classification (Figure 5). This change may be caused by anthropogenic activities that could affect mangrove density in the Sumenep area. The dominant density classes in the Sumenep area are moderate and low density. Very dense mangrove was identified only in the central part of the Sumenep area. Built-up land in Sumenep has increased, particularly in productive agricultural areas (Saputra et al. 2022).

Based on Table 3, the overall Kappa accuracy test for 40 observation points resulted in a value of 70%, indicating poor performance. The data matching the classification results and field observations included 21 points classified as very dense and 5 points as dense. The remaining 14 points showed discrepancies. One factor contributing to the differences between field observations and the NDVI mangrove density analysis results is the time discrepancy between image acquisition and field observations. High-resolution images do not necessarily ensure easier interpretation, as errors can still occur, such as differences in the timing of image acquisition and the presence of similar natural features (Naufal et al. 2022).

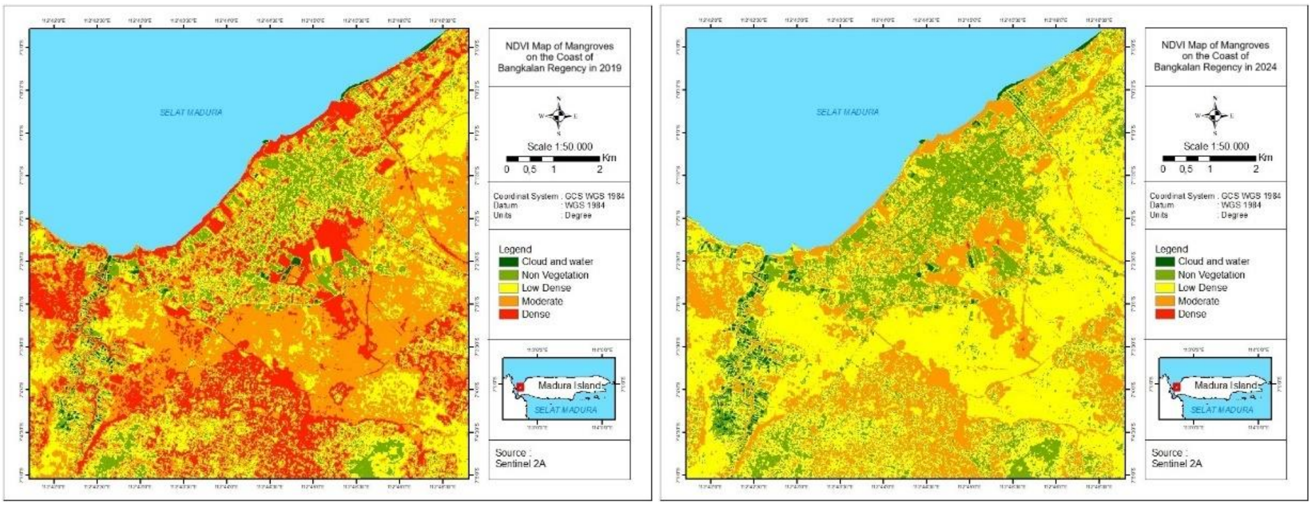

Figure 2. NDVI Map of Bangkalan Coast in 2019 and 2024

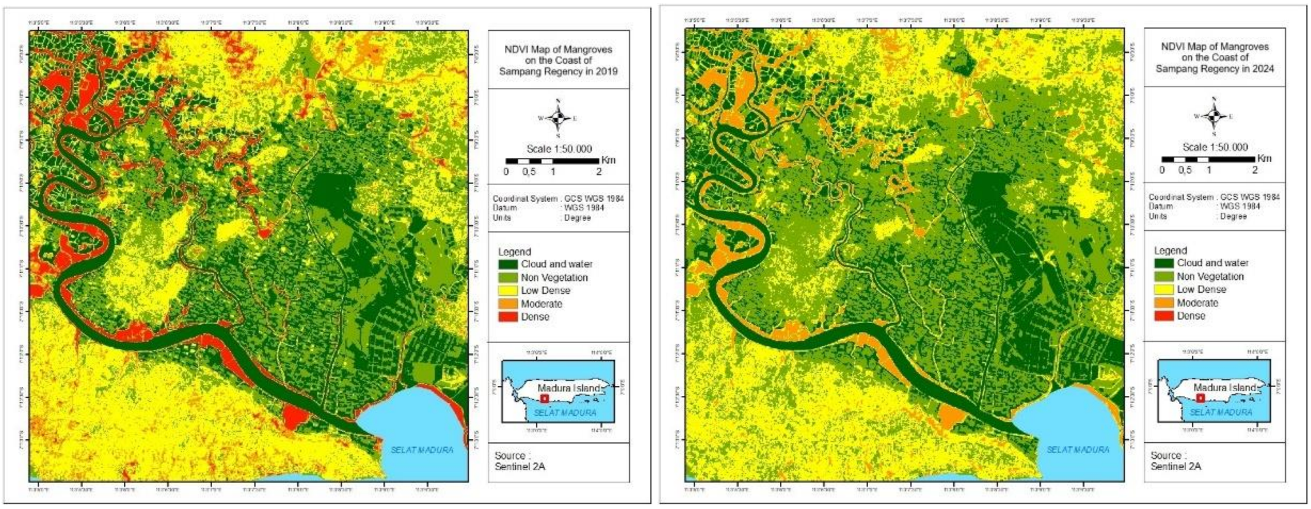

Figure 3. NDVI Map of Sampang Coast in 2019 and 2024

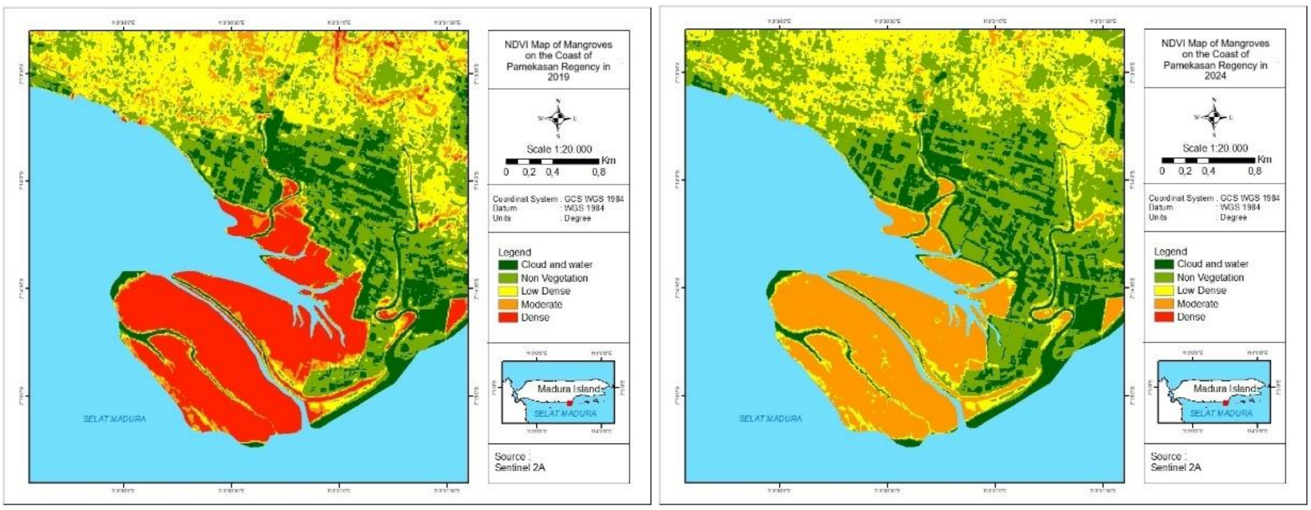

Figure 4. NDVI Map of Pamekasan Coast in 2019 and 2024

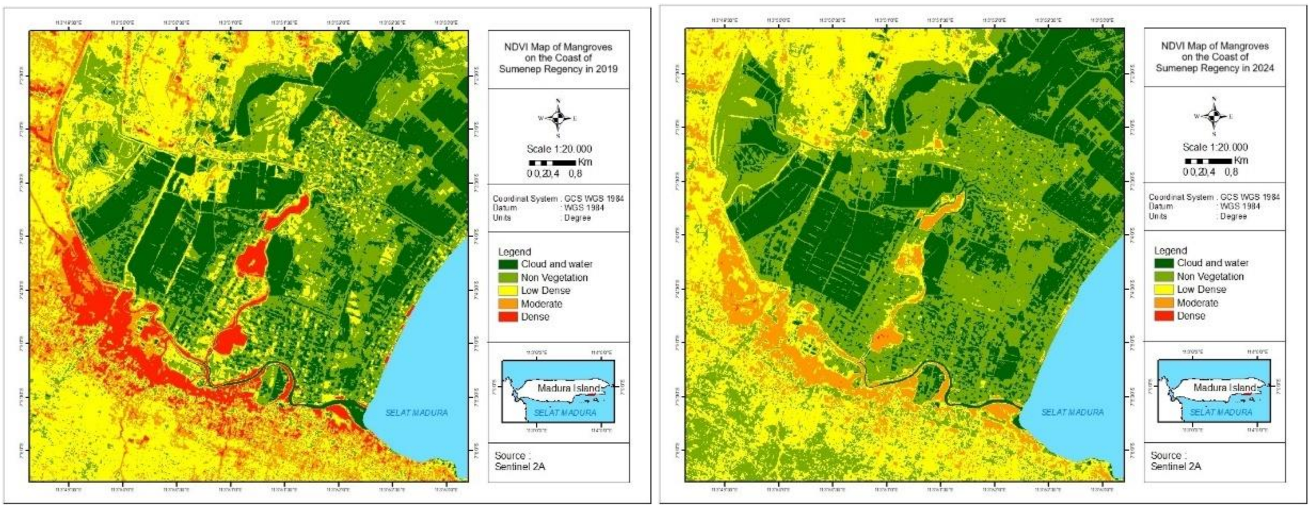

Figure 5. NDVI Map of Sumenep in 2019 and 2024

Table 3. Confusion matrix of classification results with field observation data

Mangrove density analysis	**Ground truth**						**Producer's accuracy**
	Cloud and water	**Non vegetation**	**Low dense**	**Moderate**	**Dense**	**Total**	
Cloud and water	21	0	2	0	0	23	91.3%
Non vegetation	2	5	3	0	1	11	45.5%
Low dense	2	0	0	2	1	5	0%
Moderate	0	0	0	0	0	0	0%
Dense	1	5	0	0	0	1	0%
Total	26	5	5	2	2	40	
Producer's accuracy	80.8%	100%	0%	0%	0%	70%	

Source: Kappa Analysis Results 2024

Table 4. Area (Ha) Analysis on the coasts of NDVI Classification in Bangkalan, Pamekasan, Sampang, and Sumenep

Mangrove density analysis	**Locations**							
	Bangkalan		**Pamekasan**		**Sampang**		**Sumenep**	
	2019	2024	2019	2024	2019	2024	2019	2024
Cloud and water	8.1	11.1	939.8	1,117.9	1,076.6	1,117.9	243.3	238.3
Non vegetation	52.7	10.7	1,241.0	1,319.9	1,169.0	1,319.9	140.9	299.1
Low dense	179.1	176.3	986.6	648.5	738.8	722.2	350.9	237.3
Moderate	348.9	355.3	305.4	409.3	882.5	759.3	254.1	235.1
Dense	114.7	150.1	61.8	39.2	464.6	412.3	154.3	133.8

Based on Table 4, it can be seen that in the Bangkalan area, the largest area is the mangrove region classified as moderately dense. In the Pamekasan area, the largest area is classified as non-vegetation, for example, houses, water, and vacant land. In the Sampang area, the largest area is also classified as non-vegetation. In the Sumenep area, the largest classification in 2019 was sparse vegetation, while by 2024, the largest area was classified as non-vegetated.

Discussion

2019 mangrove NDVI analysis

Mangrove areas in Madura are of significant coverage and play a crucial role in the coastal ecosystem. In 2019, the mangrove area in Madura was estimated to be declining by 1-2% per year, especially in regions under pressure from human activities (Iswahyudi et al. 2019). The total mangrove area in Madura reached 12,115.8 ha, distributed across various regions: Bangkalan with 1,508.1 ha (10%), Sampang with 915.3 ha (6,1%), Pamekasan with 599.3 ha (4%), and Sumenep, including its islands, with 12,095.4 ha (80%) (Muhsoni et al. 2019). Mangrove density in these regions can be influenced by several factors, including environmental conditions, human activities, and the mangrove species itself, such as the growth rate of mangroves and their natural regeneration ability. One of the key factors affecting mangrove density is the pressure from surrounding activities. Human activities, such as pollution from daily use, can adversely affect the environment and, in turn, influence the density of mangrove vegetation (Randa et al. 2020).

For example, salt pond activities often lead to the conversion of mangrove land into ponds, negatively impacting the density and diversity of mangrove species. This conversion reduces mangrove coverage, disrupts the ecosystem, and decreases mangrove density in the affected areas (Rachman 2024). Additionally, existing salt pond activities can cause pollution and changes in soil quality, further hindering the growth of mangrove plants (Duta 2020). Rehabilitation of land previously used as salt ponds, which is then abandoned, can contribute to the increase in density and diversity of mangrove species (Sakai 2023). The success of such rehabilitation efforts depends on effective management and public awareness of the importance of preserving mangrove ecosystems (Hardi et al. 2023).

Salt pond activities not only affect mangrove density but also have the potential to alter the structure of mangrove communities. For example, the increased nutrients derived from pond waste can influence the height distribution of mangrove plants, leading to conditions where mangroves compete with other vegetation (Armitage 2018). Conversely, such activities can also result in a decrease in species diversity (Sasmito et al. 2019). The relationship between salt pond activities and mangrove density on the coast of Madura is complex. While there is potential for rehabilitation of mangrove ecosystems, the challenges associated with managing salt ponds and maintaining sustainable mangrove density remain central concerns. Therefore, a sustainable and collaborative approach among stakeholders is crucial for ensuring the long-term health and growth of mangrove populations (Arifanti 2024). Clearing land for agriculture and plantations, such as oil palm, banana, and fish ponds, is one of the primary causes of mangrove loss. These activities often lead to the removal of mangroves and disrupt the ecological functions of the land.

Mangrove density in a region can vary, indicating that local factors influence this variation (Hasidu et al. 2021). The condition of mangrove land in Madura in 2019 was dense. This was due to factors such as species distribution, environmental conditions, soil quality, and mangrove management. The species distribution factor reveals that the presence of adaptive mangrove species, such as *R. mucronate* and *A. marina*, contributed to the increased density of the mangrove ecosystem (Tufliha et al. 2019). Additionally, environmental factors such as salinity and soil quality significantly impact the mangrove ecosystem and affect the growth of mangrove vegetation. Proper salinity conditions in a mangrove ecosystem are crucial for supporting mangrove growth (Matatula 2019). Furthermore, effective management of the mangrove ecosystem helps maintain the health of mangrove vegetation, which in turn influences the increase in mangrove ecosystem density (Adinegoro et al. 2022).

Mangrove vegetation in Madura includes several species that dominate the regions of Bangkalan, Sampang, Pamekasan, and Sumenep, such as *R. mucronata*, *A. marina*, and *Sonneratia alba*, which are commonly found species (Hamzah et al. 2021). In the Bangkalan region, *R. mucronata* was identified as the dominant species and grew well. In the Sampang and Pamekasan regions, *A. marina* became the dominant species in the mangrove ecosystem (Hamzah et al. 2021). In the Sumenep coastal area, the same species as those in the other three regions were also found. The variation in mangrove vegetation density is influenced by environmental conditions and the mangrove land management practices applied in each region (Febrianto et al. 2022).

The distribution of mangrove species in each region shows that *Rhizophora* and *Avicennia* species dominate, which is consistent with findings of mangrove species in other locations (Suryono et al. 2020). Different mangrove species exhibit varying densities and distributions, which are influenced by environmental conditions and management practices (Mardliyah et al. 2019). The interpretation of mangrove land in Madura, particularly in the regions of Bangkalan, Sampang, Pamekasan, and Sumenep, indicates that the ecosystem has a high density. However, the health of the mangrove ecosystem needs to be monitored. The health of mangrove vegetation in an ecosystem can be categorized based on the density and structure of the stands (Azzahra et al. 2023). A mangrove health assessment can be conducted by analyzing mangrove density through satellite imagery, such as NDVI, to assess canopy cover and overall ecosystem health (Tanjung et al. 2022). High mangrove density can indicate a healthy mangrove ecosystem. Increased mangrove density leads to higher litter production, generating more detritus and nutrients, thereby supporting the abundance of macro zoobenthos as a food source and attracting more benthic fauna to inhabit the ecosystem (Arfan et al. 2023).

Analysis of mangrove NDVI 2024

The coast of Madura is home to mangrove species such as *A. marina*, *R. stylosa*, and *S. alba*. In the Bangkalan coastal area, several mangrove species, such as *Avicennia alba*, *Avicennia lanata*, *Sonneratia caseolaris*, *Xylocarpus granatum*, and others, are found (Hur et al. 2020). Suitable environmental conditions support the growth of these mangrove species. *Avicennia marina* is known for its high tolerance to salinity and its respiratory roots, which enable gas exchange in anaerobic conditions on muddy substrates. *Rhizophora stylosa* thrives in muddy substrates, which are commonly found along the Madura coast. Additionally, *R. stylosa* can survive in areas with high water inundation and relatively strong currents. Its stilt root system provides stability in muddy substrates. *Sonneratia alba* is more adaptable to sandy or mixed sandy-muddy substrates, allowing it to grow well along the Madura Strait coast, where water currents bring nutrients. Its respiratory roots enable it to survive in harder substrates.

However, there has been a decline in mangrove density since 2019. This decline could be attributed to various interests of the local community, including settlement, fisheries, ports, and other activities in the area (Wardhani 2014). Dense mangrove distribution was observed along the coasts of Bangkalan, Sampang, Pamekasan, and the central area of Sumenep in 2024. The dense class is typically dominated by tree species, as the trees are relatively spaced apart (Pratama 2017). A decrease in mangrove density was also noted in other study locations, such as the coasts of Sampang, Pamekasan, and Sumenep. Anthropogenic activities may contribute to the decline in mangrove density in Sumenep. The Kalianget waters in Sumenep, located at the eastern tip of Madura Island, are used as a port area to support inter-island crossings and fishing activities.

In the coastal areas of the region, the local community has engaged in significant development activities, including land reclamation and mangrove tree cutting. These actions were taken to build salt ponds, shrimp ponds, and ports. Human activities around the waters, combined with the effects of hydro-oceanographic processes, can affect the properties, sediment distribution patterns, and shoreline changes (Nuraine et al. 2021). Mangroves on the coast of Madura grow in areas with high salinity, largely due to intensive salt pond activities. This high salinity influences the light reflection spectrum of the vegetation, resulting in lower NDVI values compared to mangroves in ecosystems less affected by extreme salinity. The expansion of salt ponds and shrimp ponds has led to mangrove fragmentation, creating uneven NDVI patterns. Areas with healthy mangroves show high NDVI values (>0.6), while degraded areas show low values (<0.3).

The mangrove ecosystem in Sampang is generally found along the coastal areas, forming a green belt. Two mangrove species dominate the region of Sampang, Madura, *Rhizophora apiculata* and *S. alba*, with trees that are not very tall. Sampang and Pamekasan are part of the coastal area, crossed by the South Coast Road. This road often experiences tidal flooding, which can affect the mangrove ecosystem in the area. Additionally, there are abiotic factors that can influence the reduction in mangrove density in Sampang and Pamekasan, such as salinity, air temperature, water pH, soil pH, rainfall, and light intensity. The Sampang area has muddy characteristics, as it faces directly toward the coast. *Sonneratia alba* is the outermost species in the region. Mangrove areas in Pamekasan have experienced a decline in density due to the large amount of plastic waste discarded by local communities, and some mangrove plants have died as a result of being cut down by the people (Lathifah et al. 2024).

Analysis of mangrove area changes in 2019 and 2024

Based on Table 4, the mangrove area in Bangkalan, Pamekasan, Sampang, and Sumenep in 2019 and 2024 has experienced both increases and decreases. The increase in mangrove area is evident in the coastal area of Bangkalan, where the moderately dense classification increased from 348.9 ha in 2019 to 355.3 ha in 2024, and the dense category increased from 114.7 ha in 2019 to 150.1 ha in 2024. The expansion of the mangrove area also occurred in the coastal area of Pamekasan, where the moderately dense classification increased from 305.4 ha in 2019 to 409.3 ha in 2024. This increase in mangrove area can be attributed to tidal changes that affect the nutrients brought along, causing mangrove vegetation near the sea or facing the sea to expand (Wilujeng et al. 2022). Another contributing factor is sedimentation. The muddy type of sedimentation, rich in organic material, supports the healthy growth of mangroves, thus increasing the size of the mangrove area. The expansion of mangrove areas along these coastlines helps stabilize the shore and prevent coastal erosion. As the area and size of mangroves increase, so do their benefits, adding value to the mangrove ecosystems in the area (As'adi et al. 2023). However, despite the growth in some areas, this increase does not compensate for the areas where mangrove coverage has decreased.

The decrease in mangrove area is more dominant compared to the increase in mangrove area (Table 4). The mangrove area in the coastal region of Madura may decrease due to both natural and anthropogenic factors. Natural factors include currents, tidal waves, and weather changes that can damage mangroves. Human-induced factors involve land conversion for various purposes, such as settlements, salt ponds, or other uses like agriculture, aquaculture, or industrial development. The Madura coast is recognized as one of the national centers for salt production (Syakatera and Purnomo 2022). The reduction of mangrove areas due to such conversions has negative environmental impacts. Ecologically, the conversion of mangrove areas leads to a decrease in ecological functions in the region. The impacts that may occur include coastal abrasion, which can cause land loss and affect shoreline changes (Zainuri et al. 2017). Furthermore, the conversion or reduction of mangrove areas can also affect the economic condition of coastal communities, as the natural resources that provide their livelihoods-such as the economic value of mangroves, mangrove crabs, shrimp, fish, etc.-are diminished (Hafni 2020).

Kappa accuracy test

The accuracy test using the kappa coefficient is frequently used to evaluate the accuracy of spatial data classification, including satellite image analysis to assess mangrove density based on vegetation indices such as NDVI (Verma et al. 2020). Kappa analysis is conducted by comparing the multispectral classification results from satellite imagery with existing field conditions to produce valid values (Wang et al. 2018). A high kappa accuracy value indicates good classification results, meaning the produced map can be used for planning and managing mangrove areas. According to the Head of the Geospatial Information Agency (BIG) Regulation No. 15 of 2014 on Technical Guidelines for Map Accuracy, the results must have an overall accuracy of ≥85% to be considered a good classification result. According to LAPAN (2015), the classification accuracy level should be ≥75%. The kappa accuracy test results in this study show a value of 70% (Table 3), which does not meet the requirements set by BIG Regulation No. 15 of 2014 (≥85%) or LAPAN USGS (≥75%). This is consistent with the research by Gumma et al. (2019), which states that accuracy values greater than 70% are considered acceptable. In contrast, the study by Mappiasse et al. (2022) on mangrove distribution in Maros in 2021 achieved an accuracy value of 86.67%. In this study, field observations on the health of mangrove forests showed a relatively high degree of agreement.

NDVI classification has weaknesses in determining the range of modes (minimum and maximum), which can lead to errors. The overlapping values make interpretation difficult, resulting in lower accuracy (Indarto et al. 2020). Significant changes in vegetation density or land cover over a short period pose a particular challenge, as the values at the Ground Control Points (GCP) may not remain constant throughout the analyzed period (Ruan et al. 2022). The accuracy value produced is related to omission error, which refers to the failure to represent objects present in the field on the map. Conversely, user accuracy is related to commission error, which occurs when objects shown on the map are not actually found in the field (Putri and Widayani 2018).

In addition to technical factors such as weather, cloud cover, and image quality, human error can also influence the NDVI Kappa accuracy calculation. Human error may occur during field data collection (ground truth), such as when the location is not representative or measurements are inconsistent (Rawson et al. 2022). Errors during the analysis phase, such as data input and calculations, should also be considered. According to Indarto et al. (2020), directly using NDVI values for classification processes is not recommended. A more comprehensive study of characteristics and specific timeframes (month or year) is needed to represent better land use variation in the field (Kurniawan and Ramadhan 2024). Mitigation measures to address these issues may include standardizing procedures with clear guidelines, conducting training and validation, and incorporating automation technologies for improved efficiency

Challenges and recommendations

Many efforts are needed to manage mangroves to maintain the sustainability of the mangrove ecosystem and ensure it functions properly. The challenges faced by mangrove ecosystems, particularly in the Madura region, are significant. One of the main challenges is land conversion for agricultural purposes and infrastructure development. The expansion of these sectors can lead to the destruction of the mangrove ecosystem (Jabbar et al. 2021). Other challenges include climate change and increased human activity, such as the use of environmentally harmful fishing practices and pollution, which negatively affect the quality and extent of mangrove areas (Adrian 2023). Improper mangrove land management can result in the loss of the ecosystem's functions, including its role in coastal protection and as a habitat for various species (Sarastika 2021).

Sustainable management strategies are essential to address future challenges and ensure the long-term health of mangrove ecosystems, particularly in the Bangkalan, Sampang, Pamekasan, and Sumenep regions. Key actions that can be taken include replanting mangroves, regulating land use, and raising public awareness about the importance of mangrove ecosystems (Arkham 2023). Through these efforts, it is hoped that the mangrove areas in these regions will remain sustainable and continue to provide benefits to the local communities.

The mangrove conservation and rehabilitation program, which includes planting activities, has been widely implemented in various regions across Indonesia and has become a government priority since 2020. This initiative is driven by the numerous benefits provided by mangrove ecosystems, including provisioning services (such as fish, clean water, and wood), regulating services (such as climate control, water purification, and disease regulation), cultural services (such as spiritual, recreational, educational, and aesthetic values), and supporting services (such as nutrient cycling, soil formation, and habitat support) (Kurniawan et al. 2024). In the research area, three key concepts- education, conservation, and community empowerment-can be adapted through appropriate environmental communication strategies. These strategies aim to ensure that the managed areas are further developed by designing activities that address the specific problems faced by local communities (Pratama 2024). Additionally, collaboration between district and provincial governments, in line with the implementation of Law No. 1 of 2014 and Law No. 23 of 2014, is crucial for promoting sustainable development, particularly in Bangkalan (Rosyid et al. 2021).

In conclusion, the mangrove areas along the coast of Madura Island from 2019 to 2024 showed some increase in mangrove cover, particularly along Bangkalan coastline. The moderately dense category increased from 348.9 ha in 2019 to 355.3 ha in 2024, while the dense category grew from 114.7 ha in 2019 to 150.1 ha in 2024. Similarly, Pamekasan coastline saw an increase in the moderately dense category, from 305.4 ha in 2019 to 409.3 ha in 2024. However, the reduction in mangrove area outweighed the increase in coverage. This decline can be attributed to factors such as climate anomalies and the conversion of mangrove land for purposes like settlements or salt ponds, which pose challenges for mangrove management in Madura. The overall Kappa accuracy result was 70%, indicating lower accuracy, with 14 out of 40 points showing discrepancies. Factors influencing this accuracy include technical aspects related to image data, such as weather conditions, cloud cover, image quality, and human error. Efforts to preserve mangrove forests in Madura should focus on improving education, conservation initiatives, and community empowerment, utilizing sustainable environmental communication strategies.

REFERENCES

Abimanyu B, Safe'i R, Hidayat W. 2019. Application of forest health monitoring method in assessing tree damage in Metro Urban Forests. Jurnal Sylva Lestari 7 (3): 289-298. DOI: 10.23960/jsl37289-298.

Adinegoro Z, Samosir A, Damar A. 2022. Ecobiology of mangrove ecosystems and their management: A case study of the conservation areas of Pulau Pramuka, Pulau Karya, and Pulau Panggang, Thousand Islands National Park. Trop Fish Manag J 6 (2): 75-86. DOI: 10.29244/jppt.v6i2.42908.

Adrian A. 2023. Pola spasial perubahan tutupan lahan/penggunaan lahan menggunakan Google Earth Engine di Kabupaten Majalengka. Jurnal Pembangunan Wilayah dan Kota 19 (4): 447-463. DOI: 10.14710/pwk.v19i4.46254. [Indonesian]

Agustin NS, Syah AF. 2020. Analisis perubahan garis pantai di Pulau Madura Menggunakan Citra Satelit Landsat 8. Juvenil: Jurnal Ilmiah Kelautan dan Perikanan 1 (3): 427-436. DOI: 10.21107/juvenil.v1i3.8843. [Indonesian]

Akbar AA, Sartohadi J, Djohan TS, Ritohardoyo S. 2017. The role of breakwaters on the rehabilitation of coastal and mangrove forests in

West Kalimantan, Indonesia. Ocean Coastal Manag 138: 50-59. DOI: 10.1016/j.ocecoaman.2017.01.004.

Arfan A, Sanusi W, Rakib M. 2023. Analysis of mangrove density and macrozoobenthos diversity in the Lantebung Mangrove Ecotourism Area, Makassar City. J Mar Res 12 (3): 493-500. DOI: 10.14710/jmr.v12i3.38060.

Arifanti V. 2024. Greenhouse gas fluxes of different land uses in mangrove ecosystem of East Kalimantan, Indonesia. Carbon Balance Manag 19 (1): 17. DOI: 10.1186/s13021-024-00263-3.

Arkham M. 2023. The value of mangrove ecosystem services availability in the Coastal Area of Dumai City. Trop Fish Manag J 7 (1): 10-20. DOI: 10.29244/jppt.v7i1.43827.

Armitage A. 2018. Nutrient enrichment shifts mangrove height distribution: implications for coastal woody encroachment. Plos One J 13 (3): e0193617. DOI: 10.1371/journal.pone.0193617.

As'adi M, Soendjoto MA, Itta D. 2023. Nilai ekonomi manfaat langsung Hutan Mangrove Pagatan Besar Kabupaten Tanah Laut Kalimantan Selatan. Jurnal Hutan Tropis 11 (1): 10-18. DOI: 10.20527/jht.v11i1.15987. [Indonesian]

Azzahra P, Sumarga E, Sholihah A. 2023. Analisis kesehatan mangrove di Taman Wisata Alam Angke Kapuk, Jakarta Utara. Jurnal Ilmu dan Teknologi Kayu Tropis 20 (1): 40-51. DOI: 10.51850/jitkt.v20i1.571. [Indonesian]

Badan Informasi Geospasial. 2014. Peraturan Ketua Badan Informasi Geospasial (BIG) No. 15 Tahun 2014 tentang Pedoman Teknis Ketelitian Peta Dasar. BIG, Jakarta. [Indonesian]

Badan Pusat Statistik Provinsi Jawa Timur. 2023. Hasil Sensus Penduduk 2023 Provinsi Jawa Timur. BPS Provinsi Jawa Timur, Surabaya. https://jatim.bps.go.id/id/statistics-table?subject=519. [Indonesian]

Dutta S. Hossain M. 2020. Bringing back the chakaria sundarbans mangrove forest of South-East Bangladesh through sustainable management approach. Asian J For 4 (2): 65-76. DOI: 10.13057/asianjfor/r040204.

Febrianto S, Syafina H, Latifah N, Puroso P. 2022. Dinamika perubahan luasan dan kerapatan ekosistem mangrove di Kawasan Taman Nasional Sembilang menggunakan Citra Satelit Landsat 8. Jurnal Kelautan Tropis 25 (3): 369-377. DOI: 10.14710/jkt.v25i3.14909. [Indonesian]

Giri C. 2021. Recent advancement in mangrove forests mapping and monitoring of the world using earth observation satellite data. Remote Sens 13 (4): 1-6. DOI: 10.3390/rs13040563.

Gumma MK, Thenkabai PS, Teluguntla P, Whitbread AM. 2019. Indo-ganges river basin Land Use/Land Cover (LULC) and irrigated area mapping. Indus River Basin 1: 203-228. DOI: 10.1016/B978-0-12-812782-7.00010-2.

Hamzah A, Anggoro S, Puryono S. 2021. Perubahan tutupan hutan mangrove menggunakan Citra Landsat 5 Tm dan 7 Etm di pesisir Kabupaten Langkat. Seminar Nasional Geomatika 2021: 771-776. DOI: 10.24895/sng.2020.0-0.1192. [Indonesian]

Hardi EH, Susmiyati HR, Diana R, Palupi NP, Agriandini M, Saptiani G, Asikin AN, Safitri MA, Sihite D, Agustina. 2023. A comparison of the silvofishery models for mangrove restoration in East Kalimantan. In Brawijaya International Conference: 614-626. DOI: 10.2991/978-94-6463-140-1_61.

Hardianto A, Dewi PU, Feriansyah T, Sari NFS, Rifiana NS. 2021. Pemanfaatan Citra Landsat 8 dalam mengidentifikasi nilai indeks kerapatan vegetasi (NDVI) Tahun 2013 dan 2019 (Area Studi: Kota Bandar Lampung). Jurnal Geosains dan Remote Sensing 2 (1): 8-15. DOI: 10.23960/jgrs.2021.v2i1.38. [Indonesian]

Hasidu LOBF, Ibrahim AF, Prasetya A, Maharani, Asni, Agustiyadin, Mubarak AA, Kamur S, Kharisma GN. 2021. Vegetation analysis, biomass estimation, and carbon stock of mangrove ecosystems in the coastal area of Latambaga District, Kolaka Regency. J Fish Sci Innov 5 (2): 60-66. DOI: 10.33772/jsipi.v5i2.9371.

Hidayah Z. 2015. Penerapan SIG dalam menentukan kondisi kritis dan model rehabilitasi ekosistem bakau pada daerah pesisir Selatan Pamekasan, Madura. Jurnal Ilmiah Perikanan dan Kelautan 7 (1): 79. DOI: 10.20473/jipk.v7i1.11238. [Indonesian]

Hidayah Z, As-syakur AR, Rachman HA. 2024. Sustainability assessment of mangrove management in Madura Strait, Indonesia: A combined use of the rapid appraisal for mangroves (RAPMangroves) and the remote sensing approach. Mar Policy 163: 106128.

Hidayah Z, Rachman HA. 2023. Pemetaan kondisi hutan mangrove di kawasan pesisir selat Madura dengan pendekatan mangrove health index memanfaatkan Citra Satelit Sentinel-2. Majalah Geografi Indonesia 37 (1): 84-91. DOI: 10.22146/mgi.78136. [Indonesian]

Hidayah Z, Suharyo OS. 2018. Analisa perubahan penggunaan lahan wilayah pesisir Selat Madura. Rekayasa 11 (1): 19-30. DOI: 10.21107/rekayasa.v11i1.4120. [Indonesian]

Hur RR, Ruchimat T, Nuraini Y. 2020. Analisis potensi dan permasalahan pengembangan wilayah pesisir di Kecamatan Arosbaya Kabupaten Bangkalan Madura Provinsi Jawa Timur. Jurnal Penyuluhan Perikanan dan Kelautan 14 (2): 137-157. DOI: 10.33378/jppik.v14i2.202. [Indonesian]

Indarto I, Nadzirah R, Belagama HR. 2020. Pemetaan lahan sub-optimal berbasis nilai NDVI Sentinel 2a: Studi pendahuluan. Jurnal Presipitasi: Media Komunikasi dan Pengembangan Teknik Lingkungan 17 (3): 194-204. DOI: 10.14710/presipitasi.v17i3.194-204. [Indonesian]

Iswahyudi I, Kusmana C, Hidayat A, Noorachmat B. 2019. Evaluasi kesesuaian lahan untuk rehabilitasi hutan mangrove Kota Langsa Aceh. Jurnal Matematika Sains dan Teknologi 20 (1): 45-56. DOI: 10.33830/jmst.v20i1.89.2019. [Indonesian]

Jabbar A, Nusantara R, Akbar A. 2021. Valuasi ekonomi ekosistem mangrove berbasis ekowisata pada hutan Desa Di Kecamatan Batu Ampar Kalimantan Barat. Jurnal Ilmu Lingkungan 19 (1): 140-152. DOI: 10.14710/jil.19.1.140-152. [Indonesian]

Kawamuna A, Suprayogi A, Wijaya AP. 2017. Analisis kesehatan hutan mangrove berdasarkan metode klasifikasi NDVI pada Citra Sentinel 2. Jurnal Geodesi 6 (2): 277-284. DOI: 10.14710/jgundip.2017.15439. [Indonesian]

Kurniawan F, Adrianto L, Yonvitner, Darus RF, Yulianto G, Tarman K, Tarigan HRC, Audriana M, Qisthi SZ, Retna DK, Pratiwi JD, Cahyo AMD. 2024. Implementasi social-ecological rehabilitation dalam mensukseskan program konservasi mangrove di Desa Tanjung, Kabupaten Sumenep, Madura. Abdimas Agro-Maritime J 2 (1): 1-14. [Indonesian]

Kurniawan M, Ramadhan A. 2024. Spatial and temporal variations in land surface temperature as an indicator of learning comfort level in Banten Province. J Geogr Sci Educ 2 (2): 42-51. DOI: 10.69606/geography.v2i2.98.

LAPAN. 2015. Pedoman Pengolahan Data Satelit Multispektral Secara Digital Supervised Untuk Klasifikasi. Pusat Pemanfaatan Penginderaan Jauh Lembaga Penerbangan dan Antariksa Nasional, Jakarta. [Indonesian]

Lathifah MN, Muazulfa TI, Nisa WK, Raharjo YAA, Arta YPA, Setyawan AD. 2024. Species diversity of mangrove at tree and pole level in Sampang And Pamekasan Districts, Madura Island, Indonesia. Indo Pac J Ocean Life 8 (2): 84-93. DOI: 10.13057/oceanlife/o080203.

Mappiasse MF, Djafar M, Asra R. 2022. Distribution of mangrove health in the coastal area of maros regency in 2021 based on sentinel 2 Satellite Imagery. Jurnal Penelitian Kehutanan Wallacea 11 (2): 165-179. DOI: 10.18330/jwallacea.2022.vol11iss2pp165-179.

Mardliyah R, Ario R, Pribadi R. 2019. Carbon storage estimation in mangrove ecosystems in Pasar Banggi and Tireman Villages, Rembang District, Rembang Regency. J Mar Res 8 (1): 62-68. DOI: 10.14710/jmr.v8i1.24330.

Martínez-Díaz MG, Reef R. 2023. A biogeographical approach to characterizing the climatic, physical and geomorphic niche of the most widely distributed mangrove species, *Avicennia marina*. Divers Distrib 29 (1): 89-108. DOI: 10.1111/ddi.13643.

Matatula J. 2019. Keragaman kondisi salinitas pada lingkungan tempat tumbuh mangrove di Teluk Kupang, NTT. Jurnal Ilmu Lingkungan 17 (3): 425-431. DOI: 10.14710/jil.17.3.425-434. [Indonesian]

Muhsoni FF, Kelautan I, Trunojoyo U. 2019. Pemetaan kerusakan mangrove di Madura dengan memanfaatkan citra dari Google Earth dan Citra LDCM. Persembahan Program Studi Ilmu Kelauatan untuk Maritim Madura 2014: 131-140.

Naharuddin N. 2021. The critical level of mangrove ecosystem in Lariang Watershed Downstream, West Sulawesi-Indonesia. Intl J Sustain Dev Plann 16 (5): 841-851. DOI: 10.18280/ijsdp.160505.

Natarajan P, Murugesan AK, Govindan G, Gopalakrishnan A, Kumar R, Duraisamy P, Balaji R, Tanuja, Shyamli PS, Parida AK, Parani M. 2021. A reference-grade genome identifies salt-tolerance genes from the salt-secreting mangrove species *Avicennia marina*. Commun Biol 4 (851): 1-10. DOI: 10.1038/s42003-021-02384-8.

Naufal N, Asriadi A, Absar S. 2022. Avoiding mistakes in drone usage in participatory mapping: Methodological considerations during the pandemic. For Soc 6 (1): 226-242. DOI: 10.24259/fs.v6i1.14117.

Noktasatria AY, Farid A. 2021. Evaluasi berkelanjutan ekosistem mangrove menggunakan rapfish di Desa Ujung Piring Kecamatan

Bangkalan Kabuaten Bangkalan. Juvenil: Jurnal Ilmiah Kelautan dan Perikanan 2 (2): 146-156. DOI: 10.21107/juvenil.v2i2.10779. [Indonesian]

Nurainie I, Wiyanto DB. 2021. Karakteristik sebaran sedimen dasar di Perairan Kalianget Kabupaten Sumenep. Juvenil: Jurnal Ilmiah Kelautan Dan Perikanan 2 (3): 243-254. DOI: 10.21107/juvenil.v2i3.11713. [Indonesian]

Nurdiansah D, Dharmawan IWE. 2021. Spatial and temporal analysis for mangrove community healthiness in Liki Island, Papua-Indonesia. IOP Conf Ser: Earth Environ Sci 944 (1): 012017. DOI: 10.1088/1755-1315/944/1/012017.

Pratama LWR. 2017. Pemetaan kerapatan hutan mangrove di Segara Anakan, Cilacap, Jawa Tengah mengunakan Citra Landsat 8 di Lembaga Penerbangan Dan Antariksa Nasional (Lapan), Jakarta. Jurnal Floratek 12 (1): 57-61. DOI: 10.17969/floratek.v12i1.7638. [Indonesian]

Pratama RP. 2024. Strategi komunikasi lingkungan ekowisata taman mangrove jung koneng Bangkalan untuk rehabilitasi. Calathu: Jurnal Ilmu Komunikasi 6 (2): 84-94. DOI: 10.37715/calathu.v6i2.4817. [Indonesian]

Putri DA, Widayani P. 2018. Aplikasi penginderaan jauh sistem informasi geografi untuk mengkaji perubahan penutup lahan dan arah perkembangan lahan terbangun di Kota Batu, Provinsi Jawa. Jurnal Bumi Indonesia 7 (3): 1-9. [Indonesian]

Rachman H. 2024. Spatio-temporal NDVI changes of mangrove forest in West Bangkalan using high resolution imagery. E3s Web Conf 499: 01032. DOI: 10.1051/e3sconf/202449901032.

Rahadian A, Prasetyo B, Setiawan Y, Wikantika K. 2019. Tinjauan historis data dan informasi luas mangrove Indonesia. Media Konservasi 24 (2): 163-178. [Indonesian]

Randa G, Lestari F, Kurniawan D. 2020. Production and decomposition of mangrove litter in Jang River Estuary, Bukit Bestari District, Tanjungpinang City. Samakia Jurnal Ilmu Perikanan 11 (11): 34-43. DOI: 10.35316/jsapi.v11i1.631.

Rawson A, Sabeur Z, Brito M. 2022. Intelligent geospatial maritime risk analytics using the discrete global grid system. Big Earth Data 6 (3): 294-322. DOI: 10.1080/20964471.2021.1965370.

Razali SM, Nuruddin AA, Lion M. 2019. Mangrove vegetation health assessment based on remote sensing indices for Tanjung Piai Malay Peninsular. J Landsc Ecol (Czech Republic) 12 (2): 26-40. DOI: 10.2478/jlecol-2019-0008.

Rizqi AAA, Ningtias AW, Nadhifah R, Aquarista DE, Nurpratiwi H. 2023. Penanaman mangrove guna mengurangi resiko banjir di Sine Kecamatan Kalidawir Tulungagung. J Creative Student Res 1 (3): 21-35. [Indonesian]

Rosadi A, Ario R, Pribadi R. 2018. Struktur dan komposisi vegetasi mangrove di Kabupaten Sampang, Pulau Madura, Provinsi Jawa Timur. J Mar Res 7 (3): 212-218. DOI: 10.14710/jmr.v7i3.25911.

Rosyid DM, Sujantoko S, Armono HD, Djatmiko EB, Wardhana W, Mulyadi Y, Kurniati N, Wardhani MK. 2021. Kajian pengelolaan kawasan mangrove pesisir selatan Kabupaten Bangkalan Berdasarkan UU No 1 Tahun 2014. SEWAGATI: Jurnal Pengabdian Kepada Masyarakat 5 (3): 206-216. DOI: 10.12962/j26139960.v5i3.26. [Indonesian]

Ruan L, Yan M, Zhang L, Fan X, Yang H. 2022. Spatial-temporal NDVI pattern of global mangroves: A growing trend during 2000-2018. Sci Total Environ 844 (2): 1-10. DOI: 10.1016/j.scitotenv.2022.157075.

Sakai Y. 2023. Recovery of mangrove ecosystem carbon stocks through reforestation at abandoned shrimp pond in Southeast Thailand. Ecosyst Health Sustain 9: 0018. DOI: 10.34133/Ehs.0018.

Saputra BAS, Pratomoatmojo NA, Jatayu A, Firmansyah F, Kusuma SH. 2022. Prediksi spasial perkembangan lahan terbangun berbasis trend dengan skenario perlindungan LP2B di Kecamatan Kota Sumenep. Jurnal Teknik ITS 11 (3): 150-156. DOI: 10.12962/j23373539.v11i3.100062. [Indonesian]

Sarastika T. 2021. Valuasi ekonomi jasa ekosistem mangrove di wilayah pesisir Kota Pekalongan. Geomedia Majalah Ilmiah dan Informasi Kegeografian 19 (1): 26-34. DOI: 10.21831/gm.v19i1.40161. [Indonesian]

Sari DP, Idris MH, Aji IML. 2022. Tingkat kerusakan kawasan mangrove di Kecamatan Lembar Kabupaten Lombok Barat. J For Sci Avicennia 5 (1): 1-12. DOI: 10.22219/avicennia.v5i1.19552. [Indonesian]

Sasmito S, Taillardat P, Clendenning J, Cameron C, Friess D, Murdiyarso D, Hutley L. 2019. Effect of land-use and land-cover change on mangrove blue carbon: A systematic review. Global Change Biol 25 (12): 4291-4302. DOI: 10.1111/gcb.14774.

Schaduw JNW. 2019. Struktur komunitas dan persentase penutupan kanopi mangrove Pulau Salawati Kabupaten Kepulauan Raja Ampat Provinsi Papua Barat. Majalah Geografi Indonesia 33 (1): 26-34. DOI: 10.22146/mgi.34745. [Indonesian]

Shiau YJ, Chiu CY. 2020. Biogeochemical processes of C and N in the soil of mangrove forest ecosystems. Forests 11 (5): 1-15. DOI: 10.3390/F11050492.

Sidik F, Supriyanto B, Krisnawati H, Muttaqin MZ. 2018. Mangrove conservation for climate change mitigation in Indonesia. Wiley Interdiscip Rev: Climate Change 9 (5): 529-537. DOI: 10.1002/wcc.529.

Suryono S, Taufiq N, Pratikto I, Ario R. 2020. Sebaran mangrove di Desa Bumiharjo Kecamatan Keling Kabupaten Jepara. Buletin Oseanografi Marina 9 (2) 117-124. DOI: 10.14710/buloma.v9i2.29067. [Indonesian]

Syakatera J, Purnomo ASD. 2022. Peran LKM sebagai sarana input produksi garam dan tenaga kerja dalam usaha tambak garam Madura. Jurnal Kajian Ilmu Manajemen (JKIM) 2 (4): 374-383. DOI: 10.21107/jkim.v2i4.18413. [Indonesian]

Tanjung CF, Yulianda F, Kurniawan F. 2023. Penilaian kesehatan mangrove di Desa Jago Jago, Kabupaten Tapanuli Tengah, Sumatera Utara. Jurnal Teknologi Perikanan dan Kelautan 14 (2): 157-167. DOI: 10.24319/jtpk.14.157-167. [Indonesian]

Tufliha A, Putra D, Amara D, Santika R, Oktavian S, Kelana P. 2019. Kondisi ekosistem mangrove di Kawasan Ekowisata Karangsong Kabupaten Indramayu. Akuatika Indonesia 4 (1): 11-25. DOI: 10.24198/jaki.v4i1.23494. [Indonesian]

Verma P, Raghubanshi A, Srivastava PK, Raghubanshi AS. 2020. Appraisal of kappa-based metrics and disagreement indices of accuracy assessment for parametric and nonparametric techniques used in LULC classification and change detection. Modeling Earth Syst Environ 6 (2): 1045-1059. DOI: 10.1007/s40808-020-00740-x.

Vu TTP, Pham TD, Saintilan N, Skidmore A, Luu HV, Vu QH, Le NN, Nguyen HQ, Matsushita B. 2022. Mapping multi-decadal mangrove extent in the northern coast of Vietnam using landsat time-series data on google earth engine platform. Remote Sens 14 (18): 1-20. DOI: 4664. DOI: 10.3390/rs14184664.

Wang D, Wan B, Qiu P, Su Y, Guo Q, Wang R, Sun F, Wu X. 2018. Evaluating the performance of Sentinel-2, Landsat 8 And Pléiades-1 in mapping mangrove extent and species. Remote Sens 10 (9): 2-27. DOI: 10.3390/rs10091468.

Wang L, Yu D, Liu Z, Yang Y, Zhang J, Han J, Mao Z. 2018. Study on NDVI changes in weihe watershed based on ca-markov model. Geol J 5 (3): 435-441. DOI: 10.1002/gj.3259.

Wardhani MK. 2014. Analisis kesesuaian lahan konservasi hutan mangrove di pesisir selatan Kabupaten Bangkalan. Jurnal Kelautan: Indones J Mar Sci Technol 7 (2): 69-74. DOI: 10.21107/jk.v7i2.799. [Indonesian]

Wasonowati C, Sulistyaningsih E, Indradewa D, Kurniasih B. 2019. Physiological characters of *Moringa oleifera* lamk In Madura. In AIP Conf Proc 2120 (1): 030024. DOI: 10.1063/1.5115628.

Wicaksono A, Wicaksono P. 2019. Geometric accuracy assessment for shoreline derived from NDWI, MNDWI, and AWEI transformation on various coastal physical typology in Jepara Regency using landsat 8 oli imagery in 2018. Geoplanning J Geomat Plann 6 (1): 55-72. DOI: 10.14710/geoplanning.6.1.55-72.

Wilujeung AD, Firdaus HG, Arianti I, Armelita A, Arifin WA. 2022. Analisis perubahan luasan vegetasi mangrove berdasarkan penginderaan jauh dan bisnis intelijen di Kawasan Muara Angke. Pena Akuatika: Jurnal Ilmiah Perikanan dan Kelautan 21 (1): 53-64. DOI: 10.31941/penaakuatika.v21i1.1572. [Indonesian]

Zainuri AM, Takwanto A, Syarifuddin A. 2017. Konservasi ekologi hutan mangrove di Kecamatan Mayangan Kota Probolinggo. Jurnal Dedikasi 14: 01-07. DOI: 10.22219/dedikasi.v14i0.4292.

Zhen J, Jiang X, Xu Y, Miao J, Zhao D, Wang J, Wang J, Wu G. 2021. Mapping leaf chlorophyll content of mangrove forests with sentinel-2 images of four periods. Intl J Appl Earth Observation Geoinformation 102: 102387. DOI: 10.1016/j.jag.2021.102387.