Oceanic index variability and its role in mangrove dieback events in East Lampung

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Abstract. A significant dieback event of Avicennia marina was observed in the coastal area of East Lampung, beginning in 2020, with its cause remaining unidentified. This study aimed to assess the rate of mangrove degradation and investigated the influence of the ocean index on mangrove dieback event. Sequential satellite imagery analysis (2019–2022) was performed to evaluate changes in mangrove cover, focusing on a 200-hectare area within the total 528.69-hectare mangrove forest, utilizing using Normalized Difference Vegetation Index (NDVI) and Mangrove Health Index (MVI). Field data were collected at 30 research stations, encompassing live mangroves, partially affected areas, and fully dieback sites, both before and during the dieback event (2020 and 2021). These efforts provide critical insights into the extent and drivers of mangrove decline in the region. Based on the results, the mangrove dieback caused a rapid and significant loss of healthy stands (results of the MVI) and very-high-density stands (results of the NDVI). With reduction in mangrove area was 117.64 ha during 2020-2021. A pronounced decline in 2021 coincided with a prolonged La Niña phase, leading to excessive freshwater influx and prolonged inundation, which likely decreased the salinity and sediment dynamics required for mangrove survival. Additionally, a negative ENSO phase (-1.2) and a concurrent positive IOD phase (+1.5) were associated with increased drought conditions, elevated salinity, and reduced freshwater availability, further stressing Avicennia marina populations. These findings underscore the strong link between oceanic variability and mangrove health, highlighting the need for continued monitoring and improved predictive models to assess the long-term impacts of climate change on coastal ecosystems.

1 Introduction

Mangroves are critical coastal ecosystems that provide numerous ecological, economic, and social benefits including shoreline protection, carbon sequestration, and habitat for marine biodiversity[1]. Despite their importance, mangrove forests face significant threats

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worldwide owing to both natural and anthropogenic factors. In recent years, East Lampung in Indonesia has experienced severe mangrove dieback, particularly affecting the Avicennia species[2]. This phenomenon has raised concerns among researchers and environmentalists regarding its underlying causes and long-term implications for the region's coastal environment.

One major factor contributing to mangrove dieback is climate variability, which influences sea surface temperature, rainfall patterns, and sea level changes. Inter-annual ocean-climate anomalies, such as the El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD), are key indicators of climate variability. These indices affect regional and global climate patterns and can lead to extreme conditions, such as prolonged droughts or excessive rainfall, both of which can be detrimental to mangrove health. [3,4].

Previous studies have demonstrated the sensitivity of mangroves to changes in salinity, water level, and nutrient availability, all of which are influenced by climate variability[5–7]. For instance, El Niño events are generally associated with reduced precipitation, leading to increased salinity and water stress in mangrove ecosystems[3]. However, in Indonesian Seas, El Niño is linked to lower seawater temperatures, which may have additional implications for mangrove health[8].

Triple-dip La Niña events that occurred from 2020 to 2022 had profound impacts on global and regional climate systems[9]. These events induce significant alterations in local hydrological conditions, exacerbating environmental stress factors in mangrove ecosystems. [2,10,11]. Understanding the role of oceanic indices in driving mangrove dieback is crucial for developing effective conservation and management strategies. In East Lampung, an active mangrove rehabilitation program has been ongoing since 2005, led by local communities that have planted over 300 hectares of mangroves, predominantly consisting of Avicennia species. However, between 2020 and 2021, more than 100 ha of these rehabilitated mangroves experienced mass dieback, raising concerns about the resilience of such ecosystems under changing climatic conditions.[12]. Many mangroves planted in East Lampung consist of monospecific stands of Avicennia species, particularly Avicennia marina and Avicennia alba. These species are well known for their high salinity tolerance, attributed to their physiological adaptations such as salt excretion through specialized glands and ultrafiltration at the root level[13,14]. However, despite their resilience to saline environments, Avicennia species exhibit limited tolerance to extreme environmental changes including prolonged inundation, hyper salinity, and abrupt shifts in hydrological regimes[15,16]. Such stressors can disrupt physiological functions, leading to reduced growth, leaf senescence, and, in severe cases, mass dieback.

This study aimed to investigate the relationship between oceanic index variability and mangrove dieback in eastern Lampung, Indonesia. By integrating multi-temporal satellite remote sensing data, conducting systematic field surveys, and employing advanced statistical analyses, this study sought to elucidate the mechanisms through which climate variability influences mangrove ecosystem health. This study hypothesizes that variability in oceanic indices, such as the Indian Ocean Dipole (IOD) and El Niño–Southern Oscillation (ENSO), significantly drives mangrove dieback events. By rigorously testing this hypothesis, this research not only advances the scientific understanding of mangrove ecosystem dynamics under climatic stress but also provides actionable insights for mitigating future dieback events and enhancing sustainable mangrove management practices.

2 Method

2.1 Study area

This study was conducted in the mangrove ecosystems of East Lampung, Indonesia, at approximately 5°21' S latitude and 105°31' E longitude, which was chosen for its significant mangrove dieback events and history of rehabilitation efforts (Fig. 1). The region is characterized by extensive mangrove forests, which are crucial for coastal protection, biodiversity, and local livelihoods. This area has been the focus of various mangrove rehabilitation efforts owing to the significant dieback events observed in recent years. The mangrove ecosystems are influenced by climatic factors, such as sea surface temperatures, rainfall patterns, and sea level changes, making it an ideal location for studying the impacts of climate variability on mangrove health.

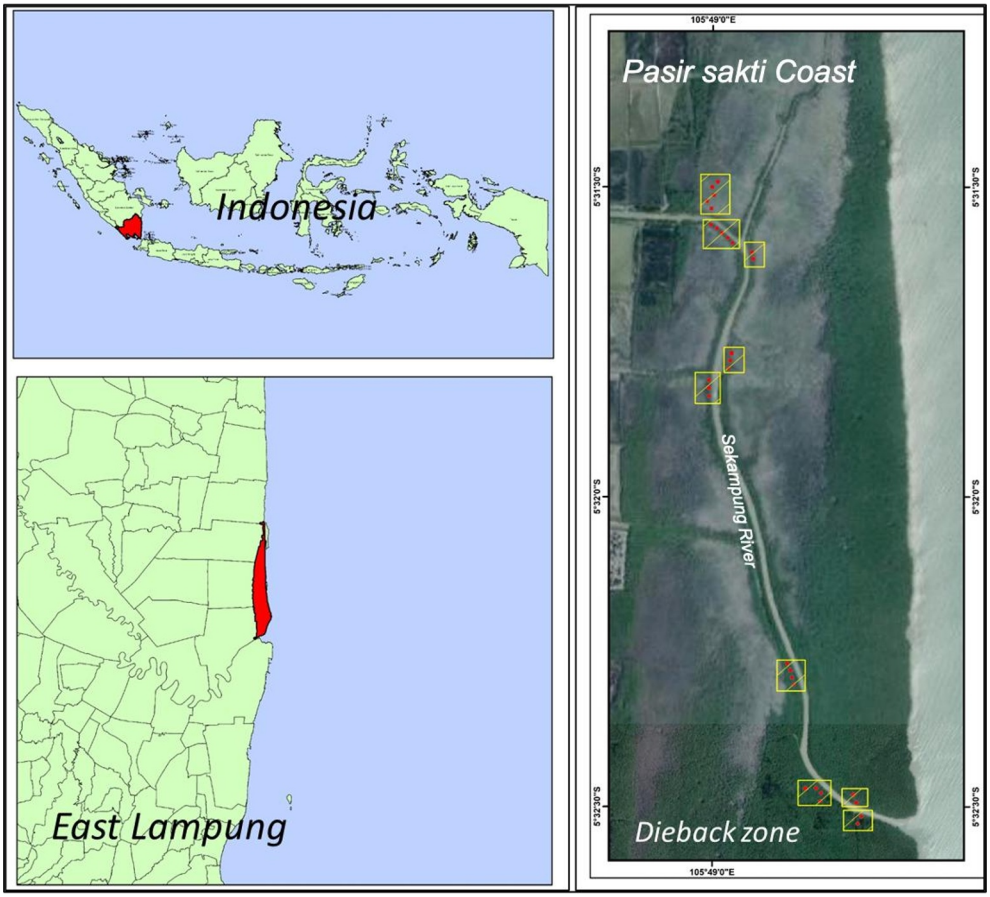

Fig. 1. The study area is in the Pasir Sakti Coast, East Lampung, Indonesia, specifically within the dieback zone. The red dots represent the observation stations for mangrove vegetation conditions and oceanographic data collection.

Table 1 summarizes the data collected, providing a comprehensive understanding of the factors contributing to mangrove dieback in East Lampung and aiding in the development of conservation strategies. The data include salinity, temperature, dissolved oxygen, and pH, which were collected through in-field measurements and samples by the research team from May 2024 to June 2024. Sea surface height data, covering the period from 2019 to 2024, were obtained from the Marine Copernicus Ocean Products. Ocean indices such as ENSO

and IOD, spanning from 2019 to 2024, were sourced from the Niño 3.4 SST Index and the Dipole Mode Index (DMI). Additionally, NDVI and MVI data derived from Sentinel-2 satellite imagery for the same period were accessed via the Copernicus Data Space Ecosystem (Table 1).

Table 1. Data used in the research.

Data Type	Time Range	Data Source
Salinity, temperature, dissolved oxygen, pH	May 2024-June 2024	In-field measurements and samples collected by the research team
Sea Surface Height	2019-2024	Marine Copernicus Ocean Products. SEALEVEL_GLO_PHY_L 4_MY_008_047 (Product ID)
Ocean index: ENSO, IOD	2019-2024	Niño 3.4 SST Index; Dipole Mode Index (DMI)
NDVI, MVI From (Sentinel-2)	2019-2024	https://dataspace.copernicus.eu/

2.2 Data Analysis

The analysis of the Mangrove Vegetation Index (MVI) and Normalized Difference Vegetation Index (NDVI) using Sentinel-2 data involves several key steps. Sentinel-2 provides high-resolution optical imagery with multiple spectral bands, including those required for vegetation analysis, such as Red, Near-Infrared (NIR), and Short-Wave Infrared (SWIR) bands[17,18]. The NDVI was calculated using the formula (NIR − Red) / (NIR + Red), where higher values indicate healthier and denser vegetation. MVI is derived from the formula (NIR-SWIR) / (NIR + SWIR), which is particularly useful for assessing mangrove health and distinguishing it from other vegetation types[17]. After extracting the relevant bands from Sentinel-2 imagery, these formulas were applied to calculate the NDVI and MVI. The resulting indices were visualized to highlight areas of high vegetation health and mangrove density. Temporal and spatial analyses of these indices can reveal changes in vegetation and mangrove cover over time, aiding land-use planning, conservation efforts, and environmental research[19]. By leveraging Sentinel-2 high-resolution data, researchers and policymakers can gain valuable insights into vegetation dynamics and ecosystem health[20].

Geospatial techniques using GIS were employed to map the spatial extent of the mangrove dieback. Satellite imagery from Landsat and Sentinel missions provided temporal data, enabling us to analyze changes in mangrove cover over time. The spatial distribution of mangrove dieback was correlated with environmental and climatic variables. This involved overlaying maps of the dieback areas with maps of soil salinity, water quality, and climate data to identify patterns and relationships.

This study employed correlation and regression analyses to examine the relationships between climatic variables (ENSO, IOD, and rainfall) and mangrove health indicators (MVI and NDVI). These analyses were instrumental in identifying the key climatic factors influencing mangrove dieback. Additionally, Principal Component Analysis (PCA) was used to reduce the dimensionality of the dataset and pinpoint the primary factors contributing to mangrove dieback. This statistical approach facilitates a deeper understanding of the variance within the data, and highlights the most significant variables affecting mangrove health[21,22].

3 Result and Discussion

3.1 Oceanic indices and Sea Surface height Variability

The temporal dynamics of ENSO and IOD indices from January 2019 to January 2024 are shown in the graph (Fig. 2). Pronounced oscillations were exhibited by both indices, indicating their influence on regional climate variability. A mangrove dieback event was marked at a specific point within the time series, suggesting a potential link between extreme climate conditions and mangrove ecosystem health. The positive phase of the IOD, as indicated by the red line, along with the concurrent [positive/negative] phase of ENSO, as shown by the blue line, is hypothesized to have contributed to the stressful conditions that triggered the mangrove dieback event. However, further analysis incorporating additional environmental factors and ground truth data is required to establish a definitive causal relationship[4,6].

The ENSO index (blue line) showed a negative phase (~ -1.5) in early 2021, indicating a La Niña event. The IOD index (red line) was also negative (~ -0.5 − -1) in early 2021, representing a negative IOD phase. The mangrove dieback event was marked from early to mid-2021. This period coincides with a strong La Niña and negative IOD, suggesting potential climatic stressors, such as cooler sea surface temperatures, altered precipitation patterns, and regional hydrological impacts[9]. La Niña and a negative IOD can cause increased precipitation and prolonged flooding, leading to salinity stress and affecting mangrove health. This can lower salinity, which is a critical factor for Avicennia marina, reducing its resilience. Excess water can limit the oxygen availability in mangrove soils, leading to root stress and mortality. A negative IOD typically weakens monsoon patterns, potentially altering tidal dynamics. The ENSO phases influence regional sea levels. La Niña can elevate sea levels and increase submersion stress on mangroves. Temperature anomalies during ENSO events may alter the metabolic and physiological responses of the mangrove species[16]. The correlation between ENSO, IOD, and mangrove dieback is likely to be driven by hydrological stress (low salinity and flooding).

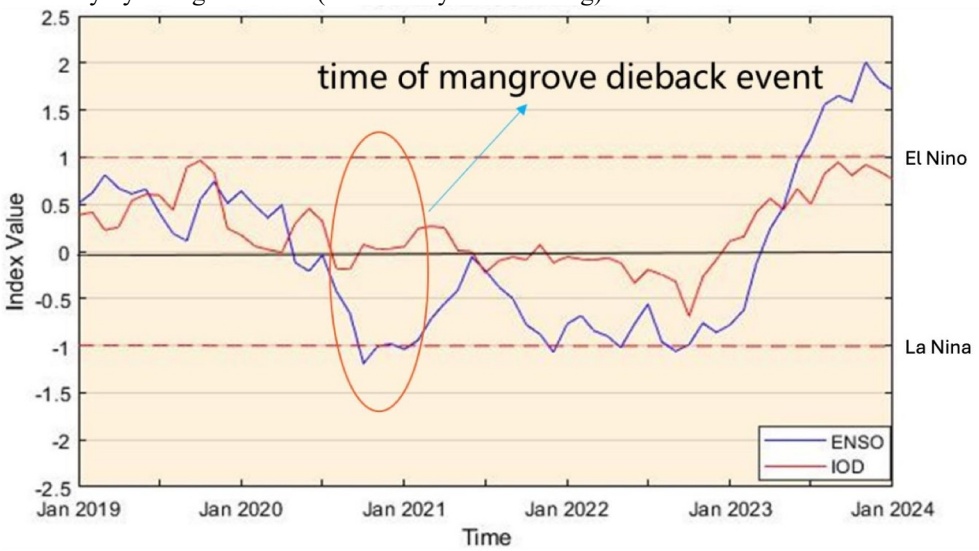

Fig. 2. The variability of the Indian Ocean Dipole (IOD) and El Niño-Southern Oscillation (ENSO) indices over time, from January 2019 to January 2024.

The annual variability of the Sea Surface Height (SSH) in East Lampung from 2019 to 2024 exhibited fluctuations that reflected dynamic oceanographic conditions (Fig. 3). The observed trends suggest potential influences of climatic events, as depicted in Figure 2. Elevated SSH in certain years might have been linked to climatic anomalies such as those caused by IOD and ENSO events. A high SSH could have led to coastal inundation, thereby affecting mangrove health and distribution[3,23].

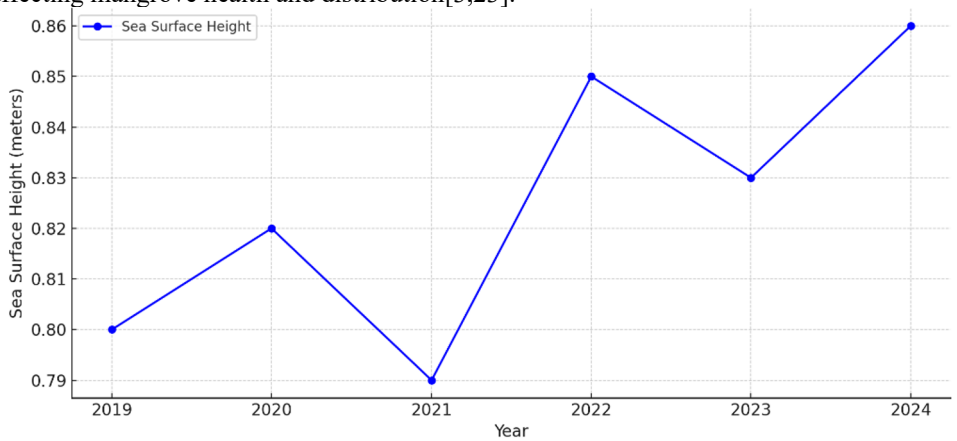

Fig. 3. Annual variability of Sea Surface Height in East Lampung (2019-2024)

The higher SSH in the study area, often linked to the positive phase of the IOD and El Niño, may be influenced by regional oceanographic and atmospheric mechanisms. While El Niño typically leads to a lower SSH in the western Pacific due to enhanced upwelling, regional effects can vary depending on monsoonal wind patterns, steric sea level changes, and oceanic circulation. In the case of East Lampung, positive IOD and El Niño events can contribute to an SSH rise through increased westerly winds, reducing coastal upwelling, and causing seawater accumulation along the coastline. Conversely, during negative IOD and La Niña periods, stronger easterly winds enhance upwelling, leading to SSH decline, increased exposure of mangrove roots, and higher susceptibility to desiccation and diseases[24,25]. The observed temporal variability in the SSH from 2019 to 2024 highlights these dynamic interactions. A more detailed analysis of SSH anomalies, particularly in 2021, when a strong La Niña and negative IOD coincided with mangrove dieback, is essential to establish a clear link between these climatic drivers and mangrove ecosystem responses.

3.2 Accumulative area of mangrove dieback dynamics

NDVI values fluctuated slightly over the years, with the lowest value in 2021 (0.66) and the highest in 2024 (0.72). This indicates a generally stable trend in mangrove vegetation health, with a slight dip in 2021, followed by recovery and improvement in the subsequent years (Table 2). Similarly, the MVI values showed a consistent increase, reflecting the overall positive trends in mangrove health and density. The slight decrease in 2021 aligns with the observed dip in NDVI, suggesting that this year might have experienced environmental stress affecting mangrove vegetation. Mangrove dieback in this region is likely to be influenced by a combination of environmental stressors and human activities. Research has shown that climate anomalies, such as the Indian Ocean Dipole (IOD) and El Niño-Southern Oscillation (ENSO), can exacerbate conditions leading to mangrove dieback, particularly through prolonged droughts, increased salinity, and sea level rise[11]. These climatic factors can cause physiological stress in mangrove trees, which makes them more susceptible to disease and mortality[8]. Moreover, human activities, including coastal development and

deforestation, may compound these effects by disrupt natural hydrology and increase the vulnerability of mangroves to environmental stressors.

Figure 4 illustrates the progression of mangrove dieback in Pasir Sakti, East Lampung, from 2020 to 2023, highlighting the significant changes in mangrove coverage over this period. The dieback, indicated by the increasing area of barren land (marked in red), reflects the severe degradation of mangrove forests. This phenomenon is particularly evident when comparing the extent of dense mangrove cover (dark green) between 2020 and 2023, where the overall area of healthy, dense mangroves has fluctuated, suggesting periods of both recovery and further loss (fig. 4).

Table 2. Annual NDVI and MVI Values for Mangrove Vegetation in East Lampung the bold text indicates changes related to mangrove dieback.

Year	NDVI	MVI	Mangrove Area (ha)
2019	0.68	0.62	301.00
2020	0.70	0.64	308.82
2021	**0.66**	**0.60**	**191.18**
2022	0.71	0.65	213.24
2023	0.69	0.63	234.41
2024	0.72	0.66	317.65

The results indicated significant temporal variability in mangrove health and spatial extent in Pasir Sakti from 2019 to 2024. The NDVI and MVI values, which serve as indicators of vegetation health and density, show a general improvement from 2019 to 2024, apart from a marked decline in 2021. This decline corresponds to a substantial reduction in mangrove area, which dropped from 191.18 hectares to 308.82 hectares in 2020. The sharp decrease in 2021 is likely attributable to adverse climatic conditions, particularly the triple La Niña event, which resulted in prolonged periods of inundation, leading to stress and subsequent dieback of the mangrove ecosystem. This period of stress highlights the vulnerability of mangroves to extreme climatic events and their impact on both the health and extent of these critical coastal habitats[8].

Despite the significant losses in 2021, the data show a recovery in both vegetation health and mangrove area in the following years, with the area reaching 317.65 hectares by 2024. The steady increase in NDVI and MVI values during this period suggests that mangroves have not only recovered but potentially expanded beyond their pre-2021 extent. This recovery may be attributed to a combination of improved climatic conditions, natural resilience of the mangrove ecosystem, and effective conservation efforts. These results underscore the importance of understanding and mitigating the impacts of climate variability on mangrove ecosystems, as well as the need for continuous monitoring and adaptive management to ensure long-term health and sustainability. [11,26]

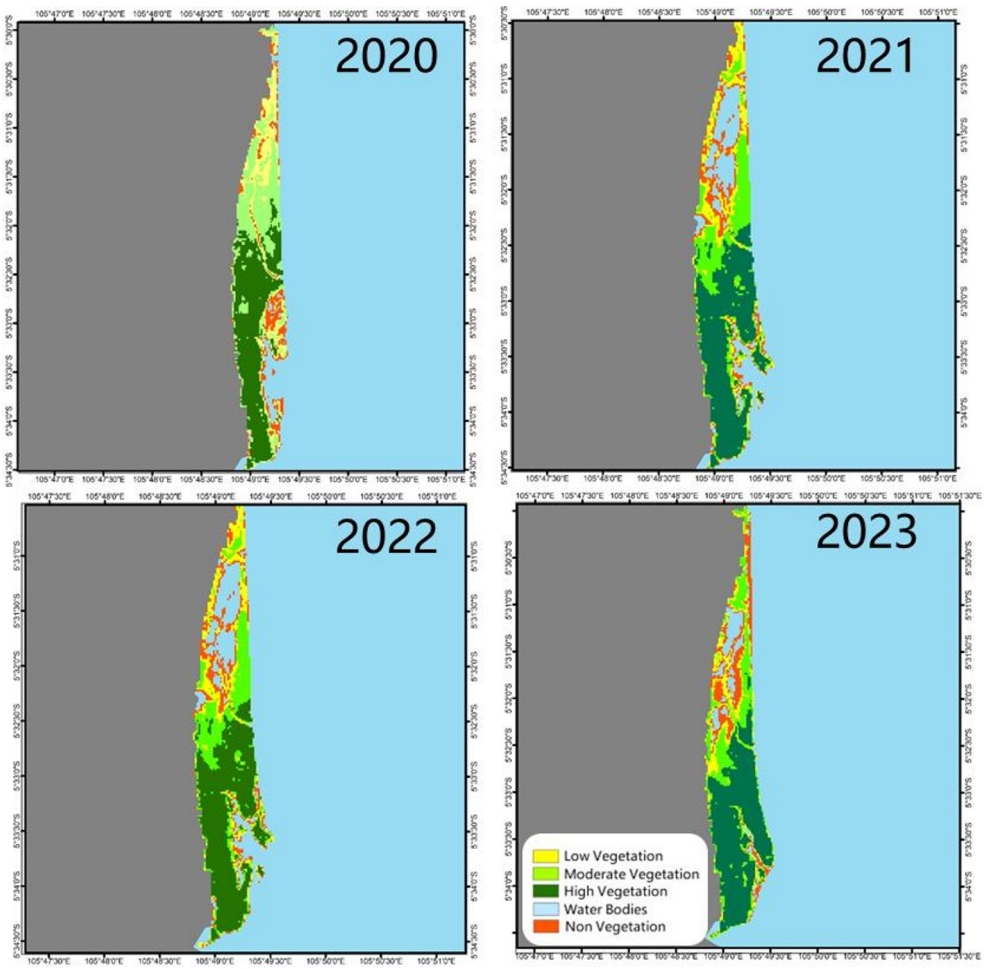

Fig. 4. Temporal Distribution of Mangrove Vegetation in East Lampung

3.3 Mangrove Dieback causes

The Indian Ocean Dipole (IOD) is a critical climatic driver in this region and is known for its significant impact on sea surface temperature (SST) anomalies and subsequent atmospheric circulation patterns. In East Lampung, fluctuations in IOD have been closely associated with variations in sea surface height (SSH) and salinity, both of which directly affect the health of mangrove ecosystems. During the positive IOD phases, warmer SSTs in the western Indian Ocean led to a higher SSH and increased moisture transport to the region. This can result in enhanced rainfall and freshwater input, creating favorable conditions for mangrove growth. However, the negative IOD phase, characterized by cooler SSTs in the western Indian Ocean and reduced rainfall, has been correlated with decreased freshwater availability and higher salinity levels, both of which impose osmotic stress on mangroves, thereby contributing to dieback[4,6].

The ENSO phenomenon, encompassing both El Niño and La Niña phases, exerts a profound influence on climate variability in Southeast Asia, including East Lampung. El Niño events are typically associated with prolonged dry conditions, reduced rainfall, and elevated temperatures, all of which exacerbate the water stress in mangrove ecosystems. The

absence of sufficient freshwater input during El Niño events can lead to increased salinity in estuarine environments, further stressing mangroves and contributing to dieback[8]. Conversely, La Niña events are characterized by cooler SSTs and above-average rainfall, which can alleviate salinity stress through increased freshwater inflows. However, excessive water input during La Niña can also result in prolonged inundation periods, which may drown mangrove roots, lead to hypoxia, and ultimately cause dieback[24,27].

PCA analysis indicated that the first principal component explained approximately 87.18% of the variance in the data, while the second principal component explained approximately 7.41%. This suggests that most of the variability in mangrove density is influenced by a combination of factors (temperature, salinity, and pH) that most strongly align with the first principal component (Fig. 5). Therefore, these factors together significantly impact mangrove density, with temperature likely being the most influential factor, based on its variance contribution.

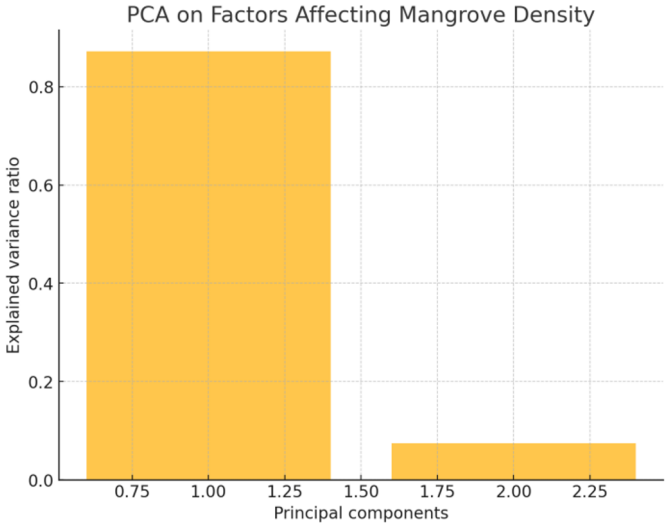

Fig. 5. Temporal Distribution of Mangrove Vegetation in East Lampung

From a physical perspective, mangrove dieback is the result of a complex interplay of environmental stressors, including sea level rise, salinity changes, temperature fluctuations, storm surges, and human-induced disturbances[28]. Each of these factors can weaken mangroves, leading to widespread dieback if stress is severe or prolonged. Understanding these physical factors is critical for developing effective management and conservation strategies to protect and restore mangrove ecosystems.

4 Conclusion

These findings indicate that mangrove dieback in East Lampung is driven by a complex interaction of environmental factors, with significant contributions from climate variability linked to the Indian Ocean Dipole (IOD) and El Niño-Southern Oscillation (ENSO), along with sea-level rise, salinity fluctuations, and temperature variability. The IOD and ENSO indices were particularly influential as they modulate critical environmental conditions that can induce osmotic stress, alter freshwater availability, and affect sea surface height, all of which are crucial to mangrove ecosystem stability. Principal Component Analysis (PCA) further elucidated that temperature, salinity, and pH are the primary determinants of mangrove density, with temperature emerging as the most significant variable. A

comprehensive understanding of these physical drivers is imperative for formulating effective management and conservation strategies to safeguard and restore mangrove ecosystems.

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