Temporal Assessment of Mangrove Restoration Success Using NDVI from Remote Sensing Data (2021–2023)

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Abstract: *Remote sensing technologies enable successful mangrove restoration monitoring because they allow the tracking of vegetation changes across large areas at affordable costs with reliable results. The Normalized Difference Vegetation Index (NDVI) serves as a reliable remote sensing index that monitors vegetation health and density, as well as ecosystem recovery. The study aims to examine the changes in NDVI values at a mangrove restoration area over three years, from 2021 to 2023, as the plants developed from seedlings into saplings. The study results demonstrated that NDVI values increased throughout the research duration, indicating successful vegetation growth and restoration. The early growth phase of 2021 showed NDVI readings between 0.077 and 0.258, which indicated that sparse vegetation was beginning to develop its canopy. The 2022 sapling stage began with NDVI values ranging from 0.134 to 0.567, indicating the onset of plant structure development and increasing vegetation density. The NDVI values in 2023 for the advanced sapling stage increased substantially from 0.261 to 0.868, indicating the formation of dense and fully developed mangrove vegetation. The research demonstrates that NDVI serves as a quantitative tool, enabling scientists to measure the progress of mangrove restoration efforts and track their growth patterns. Remote sensing technology becomes vital for maintaining long-term mangrove ecosystem monitoring systems because NDVI values increase from year to year, indicating successful ecological growth.*

Keywords: Mangrove restoration, NDVI, Remote sensing, Vegetation index

Introduction

Mangrove ecosystems function as the most productive coastal habitats, which deliver essential ecological value, economic worth, and social advantages. The coastal protection functions of mangroves, combined with their ability to store carbon and serve as fishery nurseries, protect biodiversity (Alongi, 2012). The combination of aquaculture growth, urbanization, and unsustainable resource management has led to significant degradation of ecosystem services in mangrove forests (Friess et al., 2019). The world has lost thirty percent of its mangrove forests during the last fifty years, while Southeast Asia shows the highest rate of mangrove deforestation (Hamilton & Casey, 2016). The current situation demands immediate implementation of successful mangrove restoration methods to protect both natural ecosystems and human communities.

Mangrove restoration has become a crucial conservation practice over the last several decades, helping to combat habitat loss and the impacts of climate change. The main goal of restoration activities involves creating plant development while bringing back natural ecosystem functions, which include sediment control, hydrological stability, and biodiversity conservation (Lee et al., 2019). The evaluation of restoration project outcomes requires monitoring systems that follow vegetation development across multiple time spans and geographic locations. The traditional field-based monitoring system provides useful data, yet it remains expensive and restricted to specific locations while facing various operational and financial difficulties (Ruiz-Jaen & Aide, 2005). Scientists now use remote sensing technologies because traditional monitoring methods face current restrictions, which remote sensing provides efficient, scalable, and affordable monitoring solutions.

Satellite imagery-based vegetation indices serve as strong ecological restoration tracking tools because they enable effective monitoring of vegetation health and density, as well as photosynthetic activity in vegetation (Rouse et al., 1974). The Normalized Difference Vegetation Index (NDVI) has proven effective for monitoring mangrove health and regeneration in various coastal settings (Kuenzer et al., 2011).

The tracking of NDVI changes over time becomes essential for mangrove restoration because vegetation development follows specific successional phases. NDVI values initially start at low levels when seedlings first appear due to their sparse canopy cover. However, they increase as the plants develop structural complexity and their canopies become denser (Zhang et al., 2017). The analysis of NDVI time-series data enables verification of whether restoration activities create ecological succession patterns that match natural mangrove growth patterns. The method provides quantitative evidence of project success, enabling the development of more effective restoration management approaches.

The research analyzes NDVI data from remote sensing technology to assess the progress of mangrove restoration at a restoration site between 2021 and 2023. The research examines changes in NDVI values during the seedling and sapling development stages to evaluate the success of a restoration program. The research demonstrates how NDVI patterns connect to ecological succession which enables better remote sensing monitoring of mangrove ecosystems. NDVI proves to be an effective tool for monitoring restoration progress which supports worldwide and national initiatives to protect coastal ecosystems.

Literature Review

Importance of Mangrove Ecosystems

Mangrove forests serve as vital ecosystems because they protect coastlines, manage nutrient flows, create habitats for different species, and store significant carbon reserves (Donato et al.,2011). The extensive root network of mangrove forests protects coastlines from storm surges and erosion while their leafy canopies create habitats for numerous species of wildlife. Mangrove forests generate economic value through fishing and wood extraction, producing two-fold advantages for environmental stability and socioeconomic stability (Barbier et al., 2011). The ecosystem is recognized as one of the most dynamic globally because of the constant fluctuations in physicochemical factors such as dissolved oxygen, salinity, temperature, nutrient levels, and tidal patterns, all of which play a key role in shaping the unique species diversity found in mangroves (Srilatha et al., 2013). Mangrove forests face major threats because their worldwide deforestation rate remains high due to the expansion of aquaculture, urbanization, and industrial growth (Friess et al., 2019). The identification of these threats needs the correct implementation of restoration programs and monitoring systems for their management.

Mangrove forests serve as blue carbon ecosystems, which protect against climate change while adapting to its impacts. Mangrove forests demonstrate superior carbon storage abilities compared to most terrestrial forests, as they accumulate carbon at rates up to 10 times higher, which is stored in their aboveground biomass and deep, organic-rich soil layers (Alongi, 2020; Murdiyarso et al., 2015). Mangrove stand conservation and restoration practices enable the achievement of Paris Agreement targets and Sustainable Development Goals (SDGs) because these ecosystems store carbon at an exceptional rate. Mangrove ecosystem destruction leads to greenhouse gas emissions while damaging coastal protection systems and endangering local communities, which requires urgent implementation of integrated management strategies that link environmental restoration to social and economic development (Rogers et al., 2019).

Mangrove Degradation and Restoration Efforts

The worldwide practice of mangrove deforestation has caused major damage to habitats and disrupted essential ecosystem functions (Hamilton & Casey, 2016). Climate change intensifies these existing threats by causing sea level to rise, storms occur more frequently, and changing salinity patterns that impact the health and distribution of mangroves

(Lovelock et al., 2015). The practice of restoration has become a primary approach, which includes both hydrological rehabilitation and direct tree planting (Lewis, 2005). The success rate of restoration projects depends on three main factors which include the selection of species and site conditions and natural ecological processes (Bosire et al., 2008). The practice of focusing on planting density without considering ecological needs in restoration projects has led to poor survival rates and minimal ecosystem recovery (Lee et al., 2019). Extended monitoring systems serve as essential tools for assessing restoration project outcomes because they track results that exceed the initial planting duration.

The first step for successful mangrove restoration involves understanding and fixing the core causes of degradation, which result from hydrological disturbances, aquaculture growth, and coastal development projects. Studies show that water flow restoration produces better results than big tree planting operations because it allows natural ecosystem recovery mechanisms to function (Lewis, 2005; Primavera & Esteban, 2008). The survival results of natural regeneration become better, and multiple species diversity increases when hydrological and soil conditions remain suitable. The survival of planted seedlings remains low, and ecosystem functionality remains restricted when environmental stressors are not addressed during planting operations (Kodikara et al., 2017).

Remote Sensing in Mangrove Monitoring

Remote sensing technology has transformed mangrove ecosystem monitoring by enabling extensive data collection at consistent intervals at affordable costs (Kuenzer et al., 2011). Remote sensing enables the detection of degraded mangrove areas, supports tracking of restoration efforts over time, and delivers valuable information on factors influencing mangrove health (Anu et al., 2024). Sentinel satellite data can detect vegetation changes across extensive areas over time and space, which would be impossible to achieve through traditional field surveys (Giri et al., 2011). The Normalized Difference Vegetation Index (NDVI) and other spectral vegetation indices assess mangrove forest canopy health and biomass levels, as well as monitor recovery patterns (Rhyma et al., 2020). The method provides additional ecological field data analysis, illustrating how different areas of the landscape interact with one another.

NDVI as a Restoration Assessment Tool

NDVI serves as a widely used tool to monitor vegetation changes in restoration projects that include mangrove ecosystems according to Zhang et al. (2017). The quantitative assessment of vegetation health and ecological succession becomes possible through NDVI because it measures both canopy density and photosynthetic activity. The development of mangrove vegetation from seedlings to saplings and mature canopies shows positive changes in NDVI values, according to the improvement of soil stability and ecosystem performance (Rahman et al., 2021). The ability of NDVI to track succession patterns makes it an essential tool for assessing restoration effectiveness.

The Rouse et al. (1974). NDVI measurements reveal direct relationships with biomass growth. The implementation of NDVI for mangrove restoration monitoring faces ongoing difficulties, despite current progress. The dense canopy structure of mangroves creates spectral saturation, which reduces detection sensitivity while tidal flooding impacts reflectance measurements (Xie et al., 2018). Research studies have focused on spatial patterns but they fail to examine the time-dependent restoration development. The assessment of restoration outcomes requires combining NDVI data with measurements of soil salinity and hydrological conditions to achieve complete evaluation. Research must continue to enhance NDVI-based methods while establishing their connection to complete ecosystem functions and services.

Methodology

a. Study Area

The research was conducted in Pantai Bahagia Village, Bekasi Regency, in West Java Province, Indonesia. The site requires mangrove restoration due to significant issues with coastal erosion, tidal flooding, and land subsidence. The mangrove forests at Pantai Bahagia protect the shoreline and maintain biodiversity while allowing local communities to conduct aquaculture and fishery operations. The site serves as a platform for ecological recovery research through remote sensing, as rehabilitation work has been conducted there (Amalo et al., 2024).

The study tracked mangrove development over three years, from 2021 to 2023, to observe their growth at various developmental phases. The mangrove plants began as seedlings in 2021, then developed into saplings in 2022, and reached advanced sapling development by 2023. The study area appears in Figure 1.

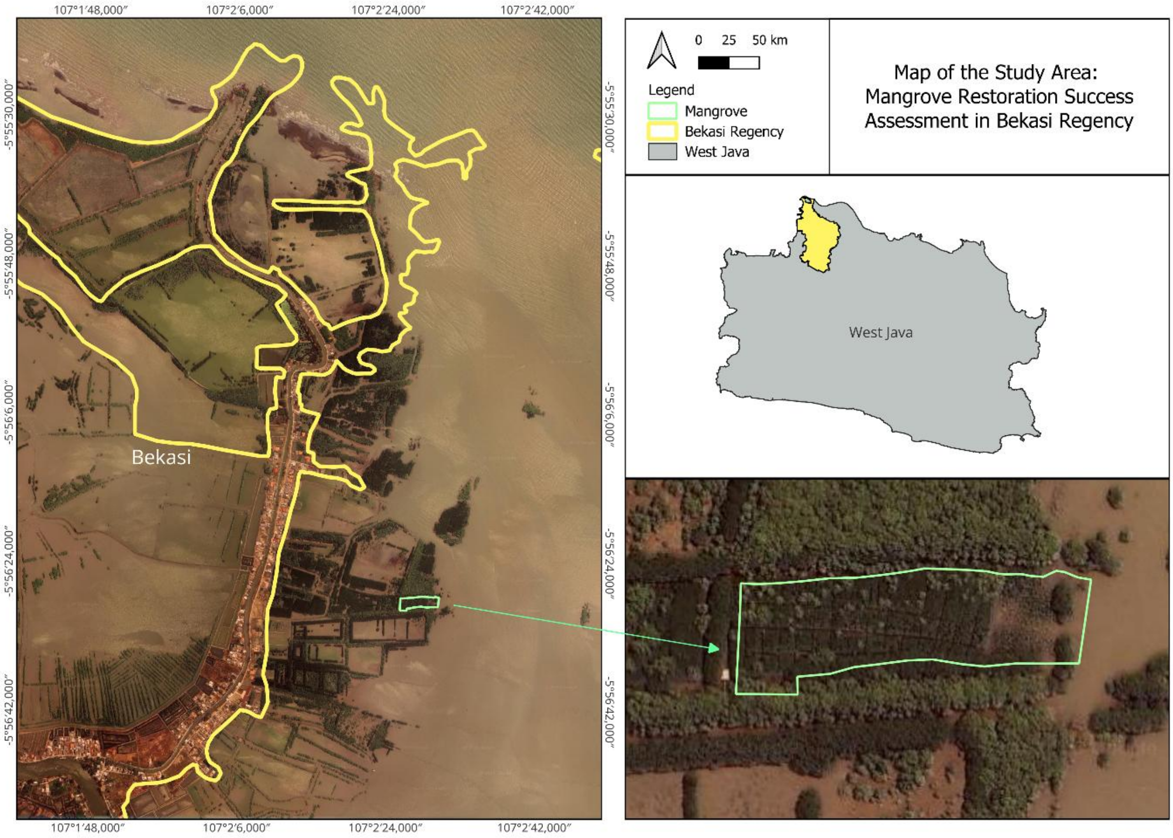

Figure 1: Study Area.

b. Data Acquisition

The research relied on Sentinel-2A multispectral imagery from the European Space Agency's Copernicus program. It has 13 spectral bands to monitor vegetation and analyze land cover through its three spatial resolution levels of 10, 20, and 60 meters (Drusch et al.,2012). The research utilized Band 4 (red, 665 nm) and Band 8 (near infrared, 842 nm) from the 10-meter visible and near infrared bands.

NDVI calculations depend on bands as their base because these bands produce superior results for vegetation monitoring. The Google Earth Engine (GEE) platform provided access to imagery data through its powerful computational capabilities for geospatial analysis (Gorelick et al., 2017). The study employed images that originated from the same time span, spanning 2021 through 2022 and 2023, to establish a yearly assessment. This study employed this method to monitor mangrove forests throughout Indonesia for both exact and reliable measurements (Amalo et al., 2024).

The Normalized Difference Vegetation Index (NDVI) functioned as the method to evaluate vegetation health together with canopy development. The calculation of NDVI is expressed in Equation (1).

$$NDVI = \frac{B8 - B4}{B8 + B4} \quad (1)$$

where B8 is expressed in near infrared reflectance (842 nm) and B4 corresponds to red reflectance (665 nm).

c. Pixel Value Extraction

The research evaluated changes in vegetation condition through the extraction of NDVI pixel values from 52 systematically distributed sampling points across the restoration site. These sampling points represent the entire mangrove area. The sampling points aim to monitor NDVI values at the same locations throughout 2021, 2022, and 2023. The restoration area underwent localized vegetation condition assessments through pixel-by-pixel measurements. We conducted descriptive statistical analysis of the extracted NDVI values using minimum and maximum value assessments, as well as calculations of mean and standard deviation.

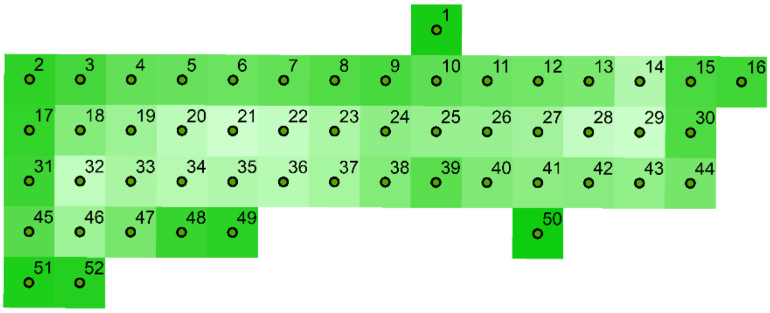

Figure 2: Pixel extraction.

Results and Discussion

The NDVI analysis of Sentinel-2A imagery from 2021 to 2023 showed that the Pantai Bahagia Bekasi mangrove restoration project produced superior vegetation structure and canopy density outcomes. NDVI serves as a reliable indicator of vegetation health, according to the scientific community, as it detects variations in chlorophyll content and photosynthetic activity (Tucker, 1979). The NDVI values showed continuous growth during the three-year period because mangrove restoration efforts in this coastal region produced increasing success.

The data in Table 1 demonstrates this time-based pattern through descriptive statistics. The NDVI measurements from the 2021 seedling stage ranged from 0.08 to 0.26. The newly planted seedlings during the early restoration phase exhibited low NDVI values because they initially had limited vegetation cover, which eventually developed into dense canopies. The NDVI values from 2022 demonstrated substantial growth, which extended between 0.13 and 0.57. The NDVI values increased during the sapling stage because vegetation spread into a solid layer as the canopy began to form a complete cover. The NDVI values from 2023 showed a major rise, which ranged between 0.26 and 0.87. The advanced saplings reached successful establishment because their leaf density increased and biomass accumulation grew while their canopy structure became more closed.

Table 1: The statistical results of the NDVI values between 2021, 2022, and 2023.

NDVI Value	**2021**	**2022**	**2023**
max	0.26	0.57	0.87
min	0.08	0.13	0.26
median	0.13	0.38	0.84

The numerical findings show the restoration area during 2021 and 2023 (Figure 3). The area exhibited minimal vegetation growth in July 2021, as indicated by low NDVI measurements throughout the area, except for a few isolated green spots. The restoration area developed into a thick mangrove forest that achieved full canopy coverage, which matched the high NDVI values from September 2023. The figure illustrates the rapid recovery of mangrove vegetation at Pantai Bahagia over the three-year period.

The NDVI value changes observed in this study align with documented ecological development patterns of mangrove rehabilitation projects found in other locations. The research by Amalo et al. (2024) demonstrated that NDVI values have a strong correlation with mangrove canopy cover, making them crucial for assessing rehabilitation success. The expansion of canopy cover indicates that vegetation density has increased, structural diversity has improved, and ecosystem function has enhanced due to effective rehabilitation methods. The rehabilitation of mangroves highlights the need to restore suitable biophysical conditions that support seedling growth, which includes constructing artificial barriers to protect seedlings from hydrodynamic energy during their establishment phase (Ellison, 2000).

The minimum NDVI value in the restoration zone increased from 0.08 in 2021 to 0.26 in 2023, indicating a significant improvement in canopy density across all vegetation levels. The improvement of weakly established areas remains essential for long-term stability of the mangrove ecosystem, as these areas tend to experience erosion and dieback (Feka & Ajonina, 2011). The maximum NDVI values increased from 0.26 in 2021 to 0.87 in 2023, indicating the development of highly vigorous vegetation patches that function as stable ecological centers, thereby enhancing the overall strength of the mangrove stand.

The vegetation recovery pattern at Pantai Bahagia aligns with established research, which indicates that mangrove rehabilitation projects typically begin to show noticeable results between three and five years after planting. Rahman et al. (2020) demonstrated comparable growth in NDVI values when they tracked mangrove recovery in Bangladesh, where canopy closure became visible after four years of restoration work. The rapid vegetation growth at Pantai Bahagia over the three years can be attributed to the combination of suitable hydrological conditions and community-based planting methods, which research has shown are essential for successful mangrove restoration in Southeast Asian waters (Alongi, 2014). The study of Twilley et al. (1999) shows that natural hydrological restoration and mangrove plantations are key factors considered important for mangrove ecosystem recovery.

These research findings show important implications for the delivery of ecosystem services. The increase in NDVI values indicates significant vegetation growth and ecosystem health as a result of restoration. The establishment of healthy mangrove forests provides multiple ecological benefits, including shoreline protection, biodiversity conservation, and carbon dioxide sequestration. The research by Alongi (2014) demonstrates that mature mangrove forests function as major carbon storage systems, which help fight climate change.

In 2021, the restoration area showed no vegetation cover and was exposed to water inundation. In 2023, the restoration area showed complete and even vegetation growth (Figure 3). The dense vegetation induced by the restoration program can enhance ecological stability and create essential habitat space for local wildlife. Nugroho et al. (2017) support these findings because they demonstrated that mangrove restoration projects create biodiversity hotspots that protect coastal areas from environmental threats. Systematic restoration work at Pantai Bahagia shows that these advantages can be reached through short-term implementation.

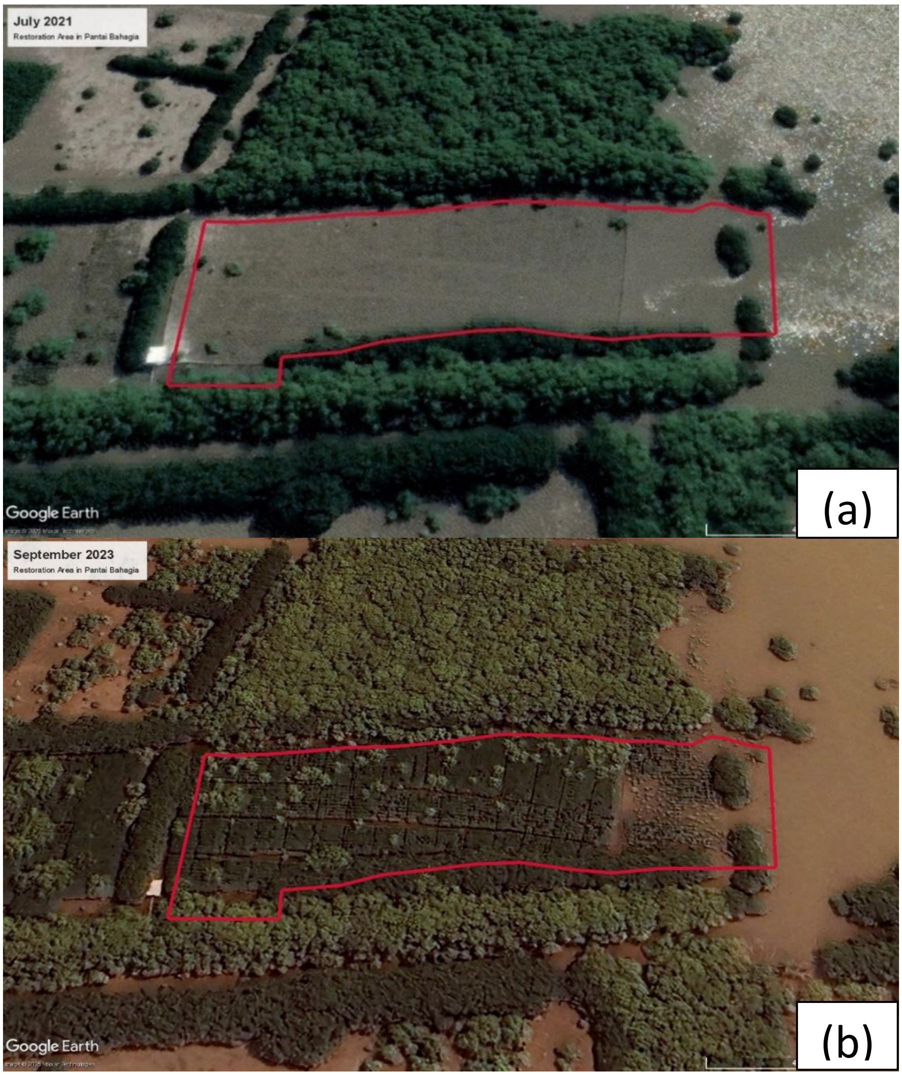

Figure 3: Comparison of the restoration area between (a) 2021 and (b) 2023.

The research confirms both the NDVI results and demonstrates how remote sensing tools effectively track mangrove ecosystems over time. The results from Pantai Bahagia demonstrate that mangrove restoration projects achieve fast ecological recovery through sustained monitoring and evidence-based management practices. The rising NDVI values indicate that rehabilitation programs are working effectively, while the combination of statistical methods with visual data and field measurements creates a comprehensive picture of environmental transformations. The research demonstrates that remote sensing technology can be effectively integrated with community-based restoration initiatives to create dual ecological and economic benefits for coastal areas.

Conclusion and Recommendation

NDVI values extracted from Sentinel-2A satellite imagery show that Pantai Bahagia Bekasi mangrove restoration projects achieved success during their first three years of operation. The mangrove seedlings from 2021 displayed low NDVI readings because their vegetation coverage remained minimal. The NDVI values from 2022 showed substantial growth because the saplings expanded their canopies. The NDVI values from 2023 reached their highest point at 0.84, which indicated that the area had transformed into a dense mangrove ecosystem with functional ecological properties.

The restoration program achieved two main goals, as indicated by statistical data, satellite images, and field observations, by protecting the planted seedlings and facilitating rapid canopy development. The ecological benefits of these improvements include better shoreline protection and superior habitat conditions, and higher carbon sequestration capabilities. The research demonstrates how NDVI serves as an effective method for tracking mangrove restoration progress through its straightforward yet dependable monitoring capabilities.

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