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Mapping Mangrove Canopy Density Changes in Pekalongan Using Sentinel-2 Red-Edge

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ABSTRACT

This study analysed spatiotemporal changes in mangrove canopy density within the coastal areas of Pekalongan Regency and Pekalongan City using multitemporal Sentinel-2 imagery (2019, 2021, and 2024). This study was motivated by the continuous degradation of mangrove ecosystems due to severe tidal flooding, land subsidence, and coastal hydrodynamic disturbances, which necessitate reliable monitoring tools to support mitigation and restoration programs. The objective of this study was to compare the performance of NDVI, NDVI-Red Edge, and mRE-SR vegetation indices in estimating mangrove canopy density and to determine the most accurate index for tidal-affected environments. The methodological framework involved image preprocessing, land cover classification, vegetation index computation, and linear regression modelling validated by in situ canopy measurements obtained through hemispherical photography. The results showed that the mangrove area declined significantly between 2019 and 2021, followed by partial recovery in 2024 in response to rehabilitation efforts. Among the tested indices, NDVI-Red Edge Band 5 yielded the highest accuracy with the lowest RMSE (7.65%), outperforming NDVI and mRE-SR, whereas Bands 6 and 7 showed weak predictive capability. The study concluded that NDVI-RE Band 5 is the most reliable index for mapping mangrove canopy density in dynamic coastal environments affected by tidal inundation. These findings demonstrate the effectiveness of combining Sentinel-2 red-edge information with field-based validation to support mangrove monitoring and coastal management.

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1. INTRODUCTION

Mangrove ecosystems play a critical role in maintaining the stability of coastal regions by functioning as natural buffers against ocean waves, reducing abrasion, preventing tidal flooding, supporting biodiversity, and sustaining coastal communities' livelihoods. Their ecological value is reflected in their ability to absorb wave energy, produce oxygen, and provide essential habitats for various marine organisms. Despite these benefits, mangrove ecosystems in Indonesia continue to experience degradation due to land conversion, overexploitation, and natural disasters (Guo et al., 2021; Hanun et al., 2021). This degradation is particularly problematic in regions where coastal hazards intensify, increasing the exposure of human settlements and public infrastructure to environmental risk.

Pekalongan, located on the northern coast of Java, has undergone severe coastal changes, resulting in significant mangrove ecosystem decline. Previous studies have indicated that the area is increasingly vulnerable to extreme tidal events and alterations in environmental characteristics that contribute to mangrove deterioration (Edifianto et al., 2021). In May 2020, a pronounced rise in sea waves inundated residential areas, causing serious losses to land, infrastructure, and coastal vegetation (Ismanto et al., 2021; Sukuryadi et al., 2021). These recurring hazards highlight the necessity of effective coastal management strategies and underscore the importance of monitoring the mangrove dynamics over time.

The primary challenge addressed in this study is the lack of continuous, accurate, and spatially explicit information on changes in mangrove canopy density in the coastal areas of Pekalongan Regency and Pekalongan City. The rapid decrease in mangrove cover due to tidal flooding has not been adequately monitored using robust and consistent methods, which limits the effectiveness of coastal mitigation strategies. Field-based monitoring alone is insufficient because of its high cost, limited coverage, and logistical constraints, making it unsuitable for large-scale and multitemporal observation needs.

To address this gap, remote sensing technology offers an effective alternative for mapping and analysing mangrove changes using satellite imagery that captures temporal variations in vegetation conditions. Recent advancements in vegetation indices, supported by studies utilising the normalised difference vegetation index (NDVI), Enhanced Vegetation Index (EVI), and red-edge-based indices, have demonstrated improved sensitivity to chlorophyll variations and canopy structure (Safitri et al., 2023; Sun et al., 2023). By integrating multitemporal satellite data and refined spectral indices, a more accurate understanding of mangrove canopy dynamics can be achieved, enabling better mitigation and conservation planning.

Previous studies have widely applied NDVI in mangrove monitoring because of its reliability in detecting vegetation greenness and canopy density. However, NDVI has limitations in distinguishing vegetation with similar greenness levels and tends to saturate under high-density canopy conditions (Safitri et al., 2023; Simarmata et al., 2021). These constraints reduce the performance of satellites in dense mangrove areas, where subtle variations in chlorophyll concentration play a crucial role. Consequently, the scientific community has increasingly explored alternative indices that leverage additional spectral information to improve vegetation sensitivity.

The development of red-edge-based indices, such as the NDVI-Red Edge (NDVI-RE), has addressed some of these limitations. Red-edge bands, particularly at wavelengths of approximately 705 nm, exhibit a higher sensitivity to chlorophyll content, enabling more precise detection of changes in vegetation conditions (Shabrina et al., 2020; Sun et al., 2023). Studies have demonstrated that the red-edge spectral region can penetrate deeper into leaf layers, making it superior for assessing dense canopies and distinguishing subtle variations in vegetation health. Furthermore, the Sentinel-2 satellite provides three red-edge bands (bands 5, 6, and 7), enhancing the potential for improved vegetation monitoring.

Another method, the Modified Red Edge–Simple Ratio (mRE-SR), combines the advantages of simple ratio approaches with the high sensitivity of red-edge wavelengths. Research indicates that mRE-SR effectively enhances vegetation discrimination and provides improved correlations with biophysical parameters, such as chlorophyll content and canopy density (Susilo & Budi, 2022). These findings support the use of red-edge-based models as reliable approaches for assessing mangrove canopy density. However, a comparative evaluation of these indices in the context of tidal-affected coastal areas remains limited, necessitating further investigation.

While studies have utilized NDVI, NDVI-RE, and mRE-SR for vegetation monitoring, their effectiveness in areas with rapid hydrodynamic changes, like Pekalongan's coastal zones, remains unexplored. Studies show potential for red-edge indices, but research on mangrove canopy density under severe tidal flooding is limited. The lack of multitemporal assessments limits understanding of canopy density changes around inundation events. A systematic evaluation of vegetation indices is needed to determine the most accurate method for mapping mangrove canopy density in dynamic coastal environments.

This study mapped changes in mangrove canopy area and density in Pekalongan's coastal region using Sentinel-2 imagery from 2019, 2021, and 2024. The novelty of this study lies in the comparison of NDVI, NDVI-Red Edge, and mRE-SR to determine the most accurate index for tidal-flood-affected mangrove monitoring. The scope of this study includes land cover classification, canopy density mapping, and vegetation index modelling supported by in situ measurements.

2. METHOD

2.1. Materials

The primary materials used in this study consisted of multitemporal Sentinel-2 satellite imagery covering the coastal areas of Pekalongan Regency and Pekalongan City, as illustrated in the research location map (Figure 1), including Sentinel-2A Level-1C acquired on November 18, 2019 (cloud cover 1.03%) and September 18, 2021 (cloud cover 5.92%), as well as Sentinel-2B Level-1C acquired on June 29, 2024 (cloud cover 14.71%), which together provided spectral information across visible, near-infrared, and red-edge bands for vegetation index analysis; supporting spatial data comprised administrative boundary and land-use shapefiles of Pekalongan Regency and Pekalongan City at a scale of 1:25,000 to delineate accurately the coastal study area shown in Figure 1, while field instruments for in situ canopy measurements included a smartphone equipped with a fisheye lens mounted on a 1-meter tripod for hemispherical photography and a GPS device for recording precise sampling coordinates, enabling consistent data acquisition, image processing, and validation throughout the study.

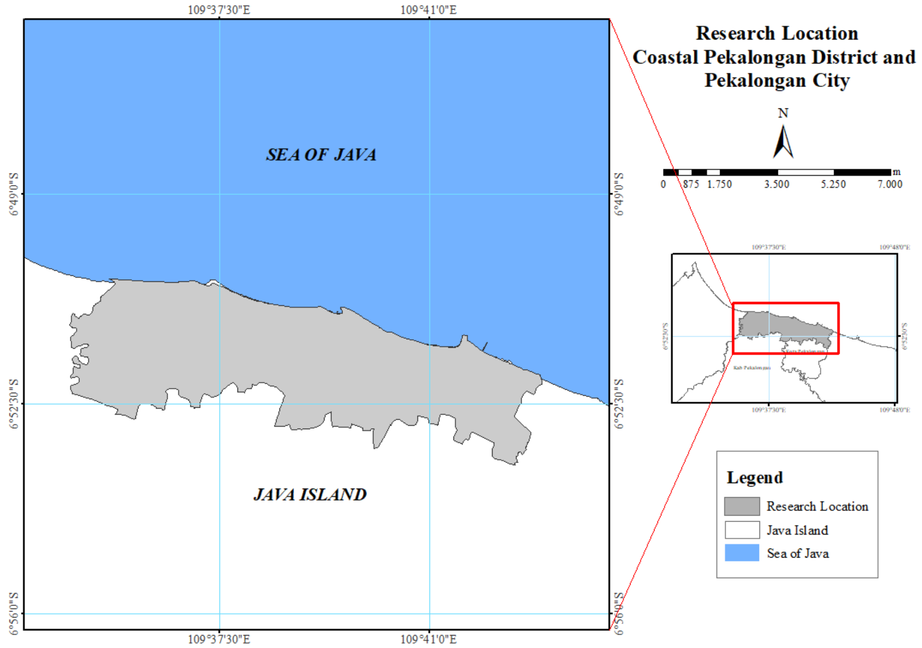

Figure 1. Map of the research location.

2.2. Sample Preparation

Sample preparation involved identifying mangrove canopy sampling points throughout the coastal region of Pekalongan. At each sampling point, three canopy photographs were taken following the cover closure approach, with the camera positioned vertically beneath the mangrove canopy. The captured fisheye images were processed using the Gap Light Analyser (GLA) software to determine canopy openness and derive the estimated canopy density percentage. The spatial coordinates of the sampling points were recorded using GPS to ensure accurate field-to-image correspondence and facilitate the validation of satellite-derived vegetation index results. All field data were organised and tabulated before being used for regression modelling.

2.3. Experimental Set-up

The experimental workflow consisted of multiple stages, beginning with satellite image preprocessing, including the resampling of red-edge bands to 20-meter spatial resolution and atmospheric correction. Land cover classification was conducted using supervised Maximum Likelihood Classification (MLC) to extract the mangrove distribution across the three observation years. Three vegetation indices were then computed: normalised difference vegetation index (NDVI), NDVI-Red Edge (NDVI-RE) using bands 5, 6, and 7, and Modified Red Edge–Simple

Ratio (mRE-SR). Multitemporal analysis was performed to quantify the changes in the mangrove canopy area.

Vegetation index computations followed standard equations:

$$NDVI = \frac{(\mathrm{NIR} - \mathrm{RED})}{(NIR + RED)} \quad (1)$$

where NIR is the near-infrared band (Band 8) and RED is the Red Band (Band 4).

$$NDVI - RE = \frac{(NIR - Red\ Edge)}{(NIR + Red\ Edge)} \quad (2)$$

where NIR is the near-infrared band (Band 8) and Red Edge is the Red Edge Band (Band 5, Band 6, Band 7). Resampling was performed to equalise the spatial resolution between bands (resampled to 20 m).

$$mRE - SR = \frac{(\frac{NIR}{Red\ Edge}) - 1}{\sqrt{(\frac{NIR}{Red\ Edge}) + 1}} \quad (3)$$

Finally, linear regression models were developed using field-measured canopy density (%) as the dependent variable and vegetation index values as independent variables to evaluate the performance of the indices for canopy density estimation.

2.4. Parameters

The parameters measured in this study included (1) mangrove canopy density derived from fisheye photography and GLA image analysis; (2) vegetation index values from NDVI, NDVI-RE, and mRE-SR computations; and (3) mangrove canopy area derived from land cover classification. Additional spatial parameters, such as tidal-affected regions, water expansion, and land conversion, were analysed to interpret the changes in mangrove distribution over time. All parameters were quantified consistently across the three years to support the comparative assessment.

2.5. Statistical Analysis

Statistical analysis involved simple linear regression modelling to evaluate the relationship between vegetation index values and field-measured canopy density. The strength of each model was assessed using the coefficient of determination (R^2) to quantify the proportion of field-based density variation explained by each of the indices. Model accuracy was further evaluated using the Root Mean Square Error (RMSE) to determine the deviation between the predicted and observed canopy density values. The index with the highest R^2 and lowest RMSE was considered the most accurate method for mapping mangrove canopy density. All statistical computations were performed uniformly across NDVI, NDVI-RE Bands 5/6/7, and mRE-SR for an objective comparison.

3. RESULTS AND DISCUSSION

3.1. RESULTS

3.1.1. Land Cover Area Change Analysis

Temporal land cover classification indicated substantial changes across the coastal areas of Pekalongan Regency and Pekalongan City between 2019, 2021, and 2024. The quantitative trends presented in Figure 2 demonstrate that the mangrove area decreased significantly by 106.22 ha from 2019 to 2021, accompanied by an expansion of water bodies by 288.98 ha, reflecting the impact of severe tidal flooding. These changes are visually supported by the combined land cover maps in Figure 4, where the 2019 and 2021 panels clearly show the conversion of mangrove and residential zones into water-dominated areas owing to prolonged inundation.

The 2024 panel in Figure 3 shows recovery across coastal segments. Mangrove cover increased by 29.61 ha while water bodies decreased by 149.56 ha, reflecting mangrove restoration by local authorities and communities. The triplet representation in Figure 3 (2019–2021–2024) captures the degradation–recovery trajectory and spatial changes over the study period.

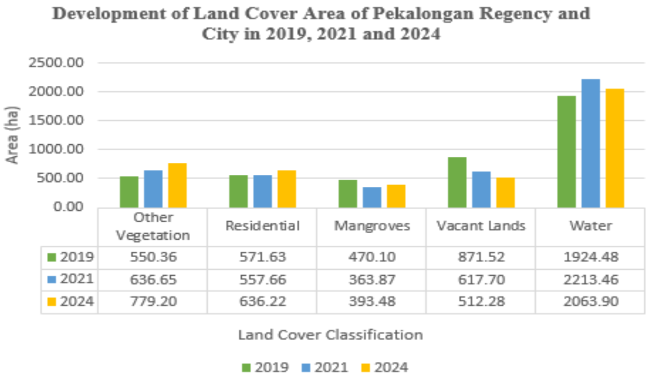

Figure 2. Land cover changes in Pekalongan Regency and City (2019, 2021, 2024).

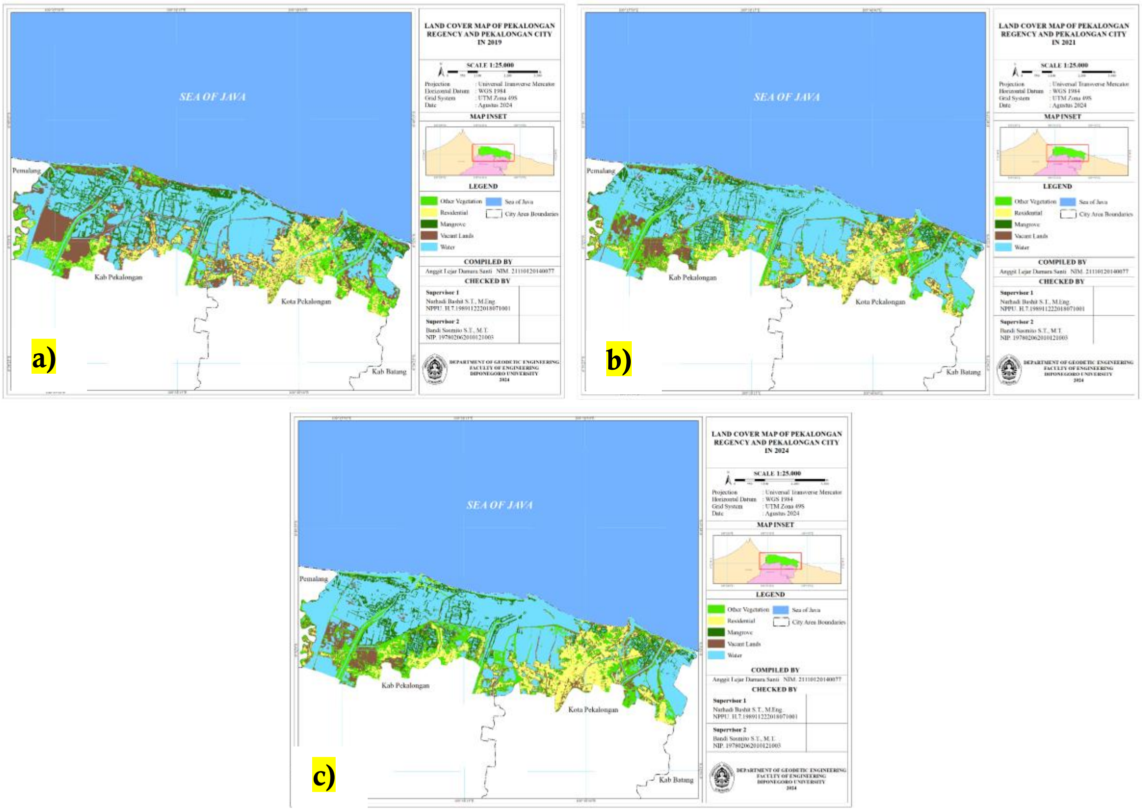

Figure 3. a) Land Cover Map of Pekalongan Regency and City in 2019, b) Land Cover Map of Pekalongan Regency and City in 2021, c) Land Cover Map of Pekalongan Regency and City in 2024

3.1.2. Mangrove Canopy Index and Density Changes

Changes in mangrove canopy conditions derived from the NDVI-red edge Band 5 index are illustrated in Figure 4, which shows a marked decline in canopy area from 2019 to 2021, followed by an increase in 2024. These temporal patterns align with the spatial distributions presented in the combined visualisation in Figure 5, where panel (a) representing 2019 NDVI-re reveals widespread moderate–high index values across several mangrove zones. Panel (b), the 2021 NDVI-re, shows the reduction of these values, corresponding to the severe tidal flooding that damaged the mangrove stands during this period.

The 2024 NDVI-re distribution shown in panel (c) of Figure 5 indicates partial recovery, with improved reflectance values appearing in several coastal segments, such as Pecakaran, Panjang Wetan, and the Jeruksari–Mulyorejo river corridors. This improvement is consistent with the increase in mangrove canopy area depicted in Figure 4 and reflects the outcomes of ongoing mangrove restoration programs.

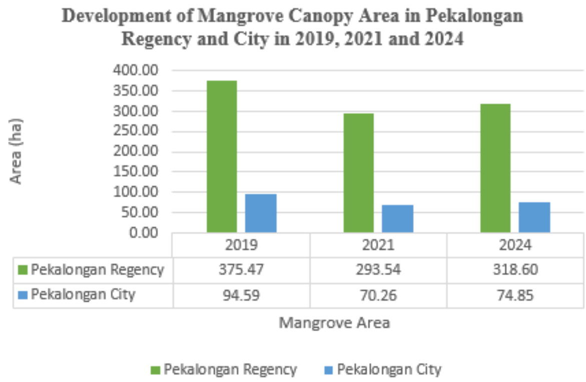

Figure 4. Diagram of Changes in Mangrove Canopy Area in Pekalongan Regency and Pekalongan City

Panel (d) of Figure 5 presents the 2019 canopy density classification, showing dominance of sparse canopy cover with limited medium- and dense-canopy patches. While the 2024 canopy density map is not included, its trend is discussed based on NDVI-re improvements in panel (c), indicating increases in medium and dense canopy classes in restored zones. The four panels in Figure 5 provide visualization of mangrove canopy degradation (2019–2021) and partial regrowth (2021–2024) in the study area.

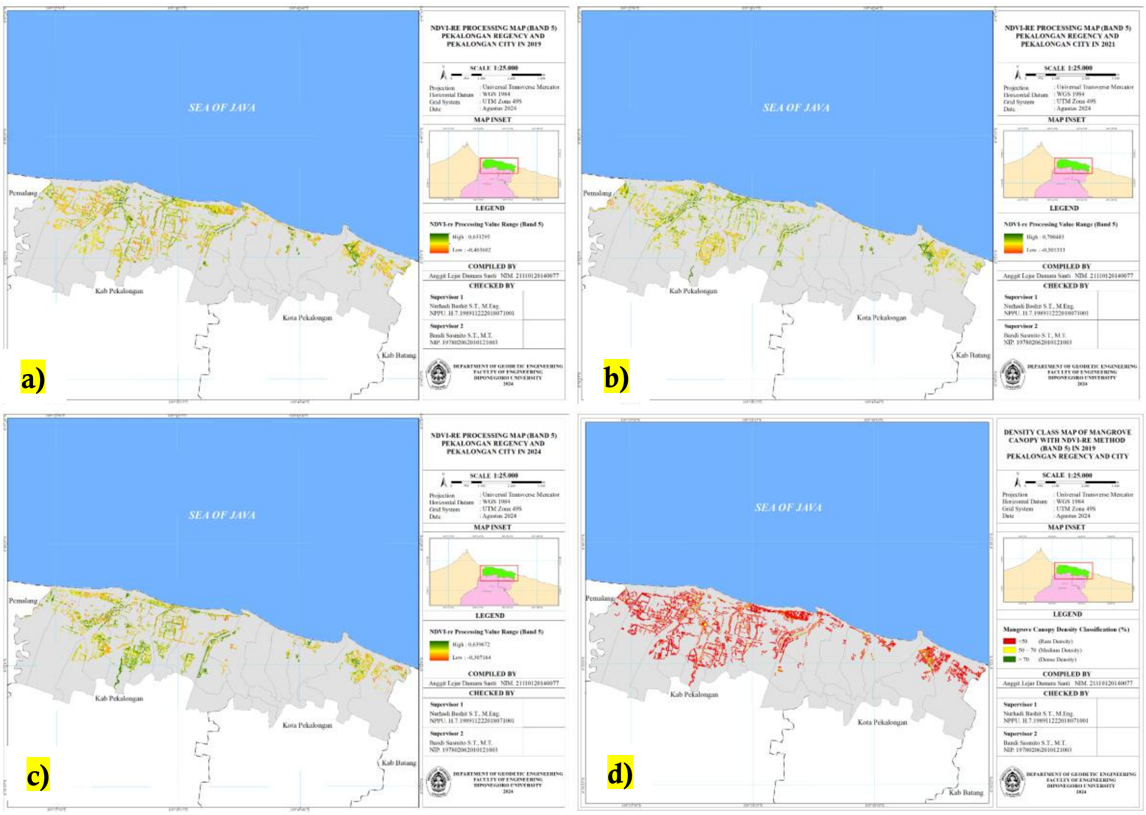

Figure 5. a) NDVI-re Band 5 Mangrove Processing Results in 2019, b) NDVI-re Band 5 Mangrove Processing Results in 2021, c) NDVI-re Band 5 Mangrove Processing Results in 2024, d) Mangrove Canopy Density Class Mapping in 2019

3.1.3. Vegetation Index Performance and Accuracy Evaluation

The performance of NDVI, NDVI-red edge bands 5–7, and mRE–SR was assessed using simple linear regression, with all models consolidated into a single visual presentation (Figure 6). NDVI-red edge Band 5 showed the strongest linear relationship with the field-measured canopy density, as indicated by the close clustering of regression points around the fitted line. NDVI and mRE–SR also demonstrated moderate predictive ability, whereas bands 6 and 7 exhibited weak correlations.

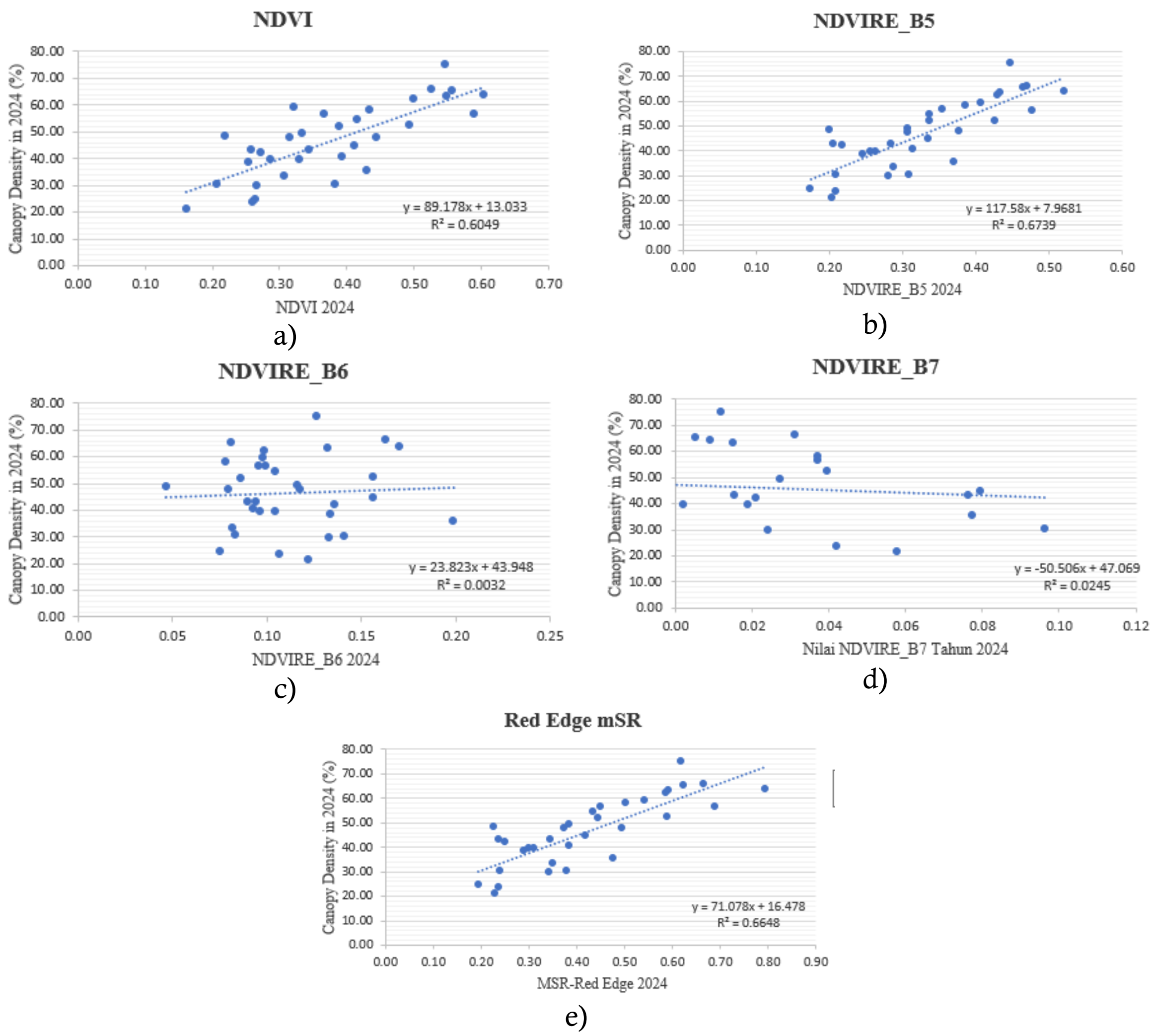

Figure 6. a) Modeling results of the method: NDVI, b) NDVI-RE Band 5, c) NDVI-RE Band 6, d) NDVI-RE Band 7, e) mRE-SR

The accuracy metrics summarised in Table 1 confirm this conclusion. The NDVI-red edge Band 5 produced the lowest RMSE (7.65%), followed by mRE–SR (7.99%) and NDVI (8.66%). The significantly higher RMSE values for bands 6 and 7 (19.16% and 19.67%, respectively) indicate that these bands are less effective for modelling mangrove canopy density. Overall, NDVI-red edge Band 5 is identified as the most accurate and reliable vegetation index for the study area.

Table 1. Root Mean Square Error Value

RMSE (%)	NDVI	NDVIRE_5	NDVIRE_6	NDVIRE_7	mRE-SR
Value	8,66	7,65	19,16	19,67	7,99

3.2. Discussion

Multitemporal land cover and canopy analyses demonstrated that the Pekalongan coastal system is highly sensitive to tidal flooding and associated hydrodynamic processes. The marked conversion of mangrove and residential areas into water bodies between 2019 and 2021 confirms previous reports that this coastline has experienced severe inundation and environmental degradation, both in terms of ecosystem conditions and socioeconomic vulnerability (Hanun et al., 2021; Ismanto et al., 2021; Wiarta et al., 2025). The subsequent increase in mangrove area and partial retreat of water bodies by 2024 shows that ecological recovery is possible when consistent restoration and management programs are implemented, in line with the role of mangroves as natural coastal protection, ecological habitats, and economic resources for local communities (Guo et al., 2021; Mahmuda et al., 2023; Rizqi et al., 2023).

The spatial pattern of degradation and regrowth visible in the NDVI-re Band 5 and canopy density maps indicates that areas exposed to persistent or higher-frequency tidal flooding, such as Bandengan and parts of Jeruksari, remain degraded despite regional gains. This is consistent with the observation that communities in these villages face recurrent tidal inundation and must continuously adapt to environmental changes (Jumatiningrum & Indrayati, 2021; Temmerman et al., 2005). Conversely, villages where planting and management were actively carried out, such as Krapyak Lor, Pecakaran, Panjang Wetan, Kandang Panjang, Degayu, and Mulyorejo, show clear improvements in medium and dense canopy classes. These findings support the view that mangrove conservation and rehabilitation, when integrated with community-based coastal management and disaster-resilient village programs, can effectively enhance ecological and social resilience (Oktavianita et al., 2020; Sulistiyono et al., 2024).

From a methodological perspective, the results highlight the advantages of combining Sentinel-2 imagery with vegetation indices that exploit the red-edge region of the spectrum. The moderate performance of NDVI and the very low explanatory power of NDVI-re Bands 6 and 7 confirm that traditional red–NIR combinations or suboptimal red-edge wavelengths may not be sufficient to capture the variability of dense and structurally complex mangrove canopies, especially under conditions of mixed pixels and background effects (Safitri et al., 2023; Simarmata et al., 2021). In contrast, NDVI-re Band 5 and mRE–SR showed higher coefficients of determination and lower RMSE, supporting earlier findings that the 705 nm red-edge band is particularly sensitive to chlorophyll content and canopy structure (Shabrina et al., 2020; Sukuryadi et al., 2021; Susilo & Budi, 2022). The superior performance of the NDVI-re Band 5 in this study therefore strengthens the argument for prioritising this band in mangrove monitoring frameworks.

The integration of in situ canopy measurements using fisheye photography and the Gap Light Analyser software with satellite-derived indices was essential for validating and calibrating the models. Although the cover-closure approach can lead to overestimation or underestimation under certain illumination and structural conditions, careful acquisition (e.g. timing near solar noon and appropriate positioning) and adequate sample replication reduce these biases and result in reliable reference data (Kusuma et al., 2023; Melo et al., 2024; Sulistiyono et al., 2022). The achieved R^2 and RMSE values indicate that, despite inevitable field and sensor noise, linear models based on NDVI-re Band 5 can estimate mangrove canopy density with errors that are acceptable for operational monitoring and planning at the landscape scale.

The findings demonstrate that red-edge-based indices are not only suitable for agricultural or upland vegetation studies, as widely reported in previous literature, but also effective for complex coastal ecosystems where canopy structure, water background, and frequent disturbance complicate spectral responses (Guo et al., 2021; Shabrina et al., 2020; Simarmata et al., 2021). Practically, the resulting maps of land cover change, NDVI-re patterns, and canopy density classes provide decision-support information for local governments to prioritise zones for protection, rehabilitation, and infrastructure planning, thereby contributing to coastal risk reduction and sustainable land use.

However, this study has several limitations. First, the analysis relies on three acquisition dates constrained by cloud cover, and additional temporal observations would improve the characterisation of seasonal and interannual variability. Second, the use of a single regression form does not capture the potentially nonlinear relationships between spectral indices and canopy structure, particularly at very high or very low densities. Future work could explore non-linear or machine-learning approaches and integrate ancillary data, such as elevation, soil, or hydrodynamic models, to better explain spatial heterogeneity in mangrove conditions. Despite these limitations, the study provides a robust demonstration that Sentinel-2 red-edge indices especially NDVI-re Band 5combined with targeted field surveys can form an efficient and relatively low-cost framework for monitoring mangrove canopy dynamics in tidal-flood-prone coastal regions.

4. CONCLUSIONS

This study successfully achieved its objective of assessing changes in mangrove canopy area and density along the coastal zones of Pekalongan Regency and Pekalongan City by utilizing multitemporal Sentinel-2 imagery and red-edge-based vegetation indices. The evaluation demonstrated that NDVI-re Band 5 is the most reliable index for characterising mangrove canopy conditions in tidal flood-affected environments, indicating its suitability for operational monitoring. The findings affirm that remote sensing provides an effective and efficient approach to support mangrove management, particularly in identifying areas requiring protection, rehabilitation, or further ecological intervention. The methodological framework established in this study offers scientific value to future coastal monitoring programs. Further research is recommended to incorporate higher-frequency imagery and advanced modelling approaches to enhance the precision and continuity of mangrove canopy assessments.

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