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Research Article

Mangrove Forest Density Mapping Using Google Earth Engine in Deli Serdang Regency

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Abstract: Mangrove ecosystems play a crucial role in maintaining coastal stability, supporting biodiversity, and sustaining local livelihoods. However, increasing environmental pressure and human activities have led to changes in mangrove cover and vegetation structure in Deli Serdang Regency. This study aims to analyze changes in mangrove cover area and density between 2020 and 2024, as well as to identify the factors influencing these changes. The research employs a qualitative descriptive approach supported by spatial analysis using Sentinel-2A imagery processed through Google Earth Engine and the Normalized Difference Vegetation Index method. Field validation was conducted using purposive sampling and GPS-based ground truth data to assess classification accuracy. The results show that mangrove cover decreased from 13,694 ha in 2020 to 13,173 ha in 2024. A significant shift in vegetation structure was observed, with dense mangrove areas declining from 61% to 42%, while moderate-density areas increased from 15% to 33%. The classification achieved an overall accuracy of 83% with a Kappa coefficient of 0.76, indicating reliable results. Environmental factors such as water pH and substrate type, along with anthropogenic pressures including land conversion and accessibility, were identified as key drivers of mangrove density changes. These findings highlight that mangrove degradation occurs not only through area reduction but also through structural changes in vegetation density. The study implies that remote sensing-based monitoring combined with field validation provides an effective approach for supporting sustainable mangrove management and conservation strategies in coastal regions.

Keywords: Mangrove Density; NDVI; Sentinel-2A; Remote Sensing; Coastal Ecosystem.

1. INTRODUCTION

Mangrove forests are vital coastal ecosystems that serve as natural barriers against shoreline erosion and tsunami impacts, while also supporting biodiversity and providing essential livelihood resources for surrounding communities (Afriansari et al., 2024). These ecosystems serve as breeding, nursery, and feeding grounds for various marine and terrestrial species, making them crucial to coastal ecological stability. In addition, mangroves contribute significantly to carbon sequestration, often referred to as “blue carbon,” which plays an important role in mitigating climate change (Alongi, 2020). In Indonesia, one of the countries with the longest coastlines in the world, mangrove ecosystems are widely distributed and represent the second-largest mangrove area globally after Brazil (Manan, 2020). Mangroves play a strategic role in maintaining coastal resilience and ecological balance. However, these ecosystems are increasingly threatened by deforestation, land conversion for aquaculture and settlements, and other anthropogenic pressures that accelerate environmental degradation (Ermgassen et al., 2020).

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Changes in mangrove land cover driven by both human activities and natural factors have reduced the extent and quality of these ecosystems, which in turn negatively affect their ecological functions and biodiversity (Galvanis et al., 2024). The loss of mangrove coverage not only reduces habitat availability for flora and fauna but also diminishes coastal protection capacity, increasing vulnerability to natural disasters. Furthermore, degradation of mangrove ecosystems can disrupt local socio-economic systems, particularly for communities that depend on fisheries and coastal resources (Dittmann et al., 2022). Therefore, the availability of up-to-date, periodic mapping of mangrove conditions is highly essential. Such spatial information can support evidence-based decision-making, facilitate monitoring and evaluation of conservation programs, and guide policymakers in designing sustainable coastal management strategies (Ruruh & Suma, 2024).

The advancement of remote sensing technology has provided powerful tools for mapping and monitoring land-cover changes efficiently and cost-effectively (Singh, 1989; Jensen, 2015). One of the most significant innovations in this field is Google Earth Engine, which provides extensive access to satellite imagery archives and enables large-scale geospatial analysis in near real time without requiring high-end computing infrastructure (Gorelick et al., 2017; Fikri et al., 2019). This platform allows researchers to efficiently process and analyze multi-temporal satellite data, making it particularly useful for environmental monitoring. The integration of satellite imagery such as Sentinel-2A, which provides high spatial resolution and multispectral data, enhances the accuracy of mangrove mapping and supports detailed analysis of vegetation characteristics (Puig et al., 2019).

The implementation of GEE-based methods using vegetation indices, particularly the Normalized Difference Vegetation Index, enables rapid and precise detection of mangrove density levels (Silveira et al., 2021; Lazuardi et al., 2021). NDVI is widely used to assess vegetation health and coverage by analyzing the difference between near-infrared and red spectral bands, making it highly effective for distinguishing dense, moderate, and sparse mangrove areas (Charrua et al., 2021). This approach facilitates continuous monitoring of land-cover changes over time and enables researchers to identify patterns of degradation or regeneration within mangrove ecosystems (Chen et al., 2025). In the context of Deli Serdang Regency, the application of this technology is particularly relevant given the region's dynamic coastal environment and the growing need for accurate spatial data to support sustainable management practices.

Based on these conditions, this study aims to map the density levels of mangrove forests in Deli Serdang Regency for 2020 and 2024 using Google Earth Engine and Sentinel-2A imagery, and to analyze the factors influencing these changes. By integrating spatial analysis with temporal comparison, this research seeks to provide a comprehensive understanding of mangrove dynamics in the study area. The findings are expected to provide accurate, up-to-date information that can serve as a scientific basis for policymakers, stakeholders, and local communities to develop more effective and sustainable mangrove conservation and management strategies.

2. RESEARCH METHODS

Research Design

This study employs a descriptive quantitative approach combined with spatial analysis to examine changes in mangrove density and distribution over time. The research integrates satellite image processing, field surveys, and statistical analysis to produce comprehensive and accurate findings. A time-series analysis is applied to compare mangrove conditions between 2020 and 2024, enabling the identification of spatial patterns and ecological changes. The use of geospatial technology and vegetation indices strengthens the analytical framework.

Research Location and Time

This research was conducted in Deli Serdang Regency, an area characterized by extensive mangrove ecosystems that have undergone notable land-cover changes in recent years. The region was selected due to its variation in mangrove density and degradation levels. The study was carried out from January 2024 to April 2024, covering stages of data collection, processing, and analysis.

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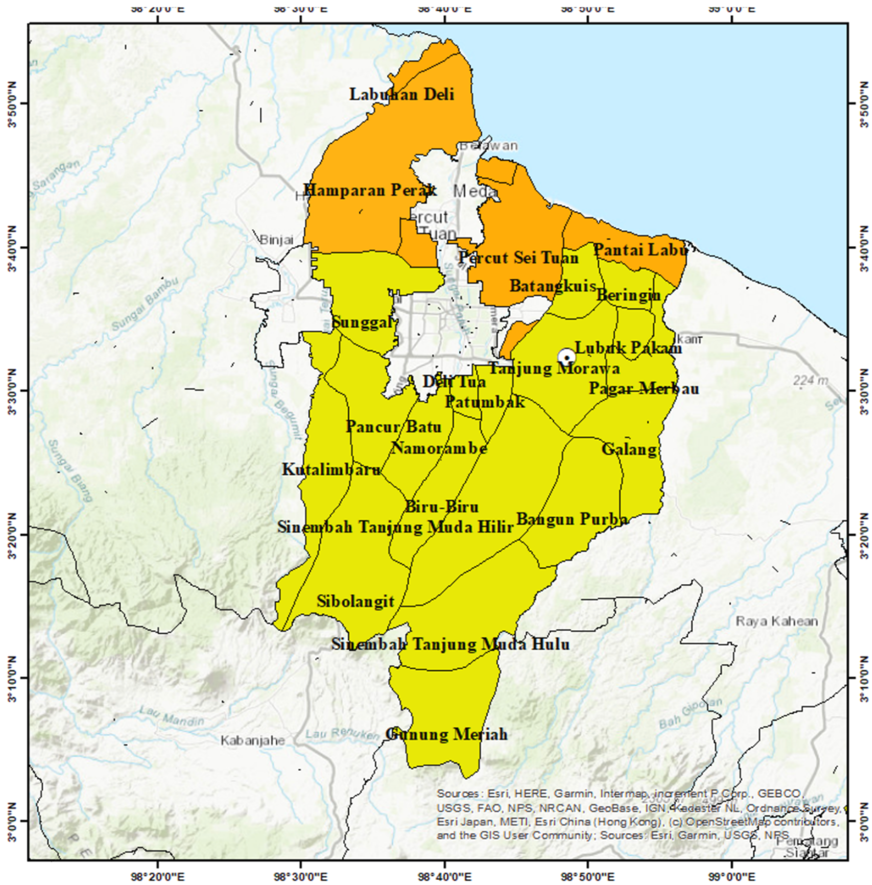

Figure 1. Map of Mangrove Areas in Deli Serdang Regency (Source: Data Processing, 2025)

Figure 1 illustrates the distribution of mangrove ecosystems in the coastal areas of the study region. The research focuses on four sub-districts with varying mangrove density and environmental dynamics: Hamparan Perak, Percut Sei Tuan, Pantai Labu, and Labuhan Deli. The method applied combines survey-based approaches with satellite image processing and spatial analysis. Primary data were obtained from Sentinel-2A imagery via the Google Earth Engine platform, which was used to derive mangrove density levels from vegetation indices. Supporting data were collected through field surveys using purposive sampling techniques and GPS instruments to ensure the accuracy of field observations and classification maps generated from image analysis.

Population and Sample

The population in this study includes all mangrove areas located within the four sub-districts of Deli Serdang Regency, namely Hamparan Perak, Percut Sei Tuan, Pantai Labu, and Labuhan Deli, particularly for map accuracy assessment. The sample was determined using purposive sampling, considering areas representing different levels of mangrove density (dense, moderate, and sparse) and site accessibility. This sampling technique was intentionally applied based on regional characteristics and the availability of relevant field data.

Tools and Materials

The tools used in this study include field equipment such as GPS (Global Positioning System), writing instruments, classified mangrove maps, documentation cameras, and computers/laptops equipped with data-processing software such as Microsoft Office 2016 and ArcGIS. The primary materials consist of Sentinel-2A imagery and mangrove classification maps derived from image analysis. These tools and materials support both spatial analysis and field verification processes to ensure data reliability and accuracy.

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Research Workflow

The initial stage of the study involved collecting satellite imagery from 2020 and 2024, followed by image interpretation and classification using the maximum likelihood method to determine mangrove density levels based on the Normalized Difference Vegetation Index. The classification results were then validated through field surveys, in which samples were collected using purposive sampling, taking into account accessibility and varying density levels. Subsequently, the field data were analyzed quantitatively using descriptive statistics and image interpretation to characterize changes in mangrove coverage area and distribution by density level. This analysis aims to identify spatial distribution patterns and ecological changes in mangrove ecosystems through a systematic approach integrating spatial data and direct observations. The formula used to calculate the percentage of mangrove density or related variables is as follows:

$$P = (Xi / X) \times 100\%$$

Where:
P = percentage related to mangrove density or specific measurement
Xi = number of samples or area meeting certain criteria
X = total samples or total area analyzed

The results of the analysis were then processed and presented as tables, graphs, and thematic maps to illustrate trends in mangrove changes and the factors influencing their density within the study area. Descriptive statistical analysis and image interpretation were applied to measure shifts in distribution and ecosystem conditions over the observed period. Therefore, this method integrates satellite image processing, field observations, and statistical and spatial analyses to provide a comprehensive understanding of mangrove conditions and the factors influencing their ecological dynamics.

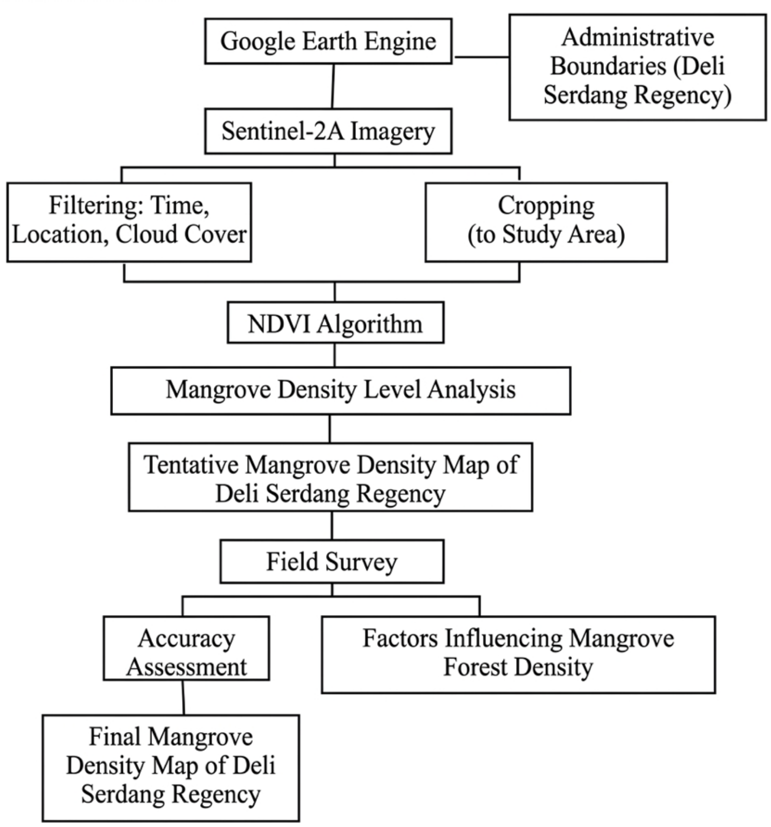

Figure 2. Data Processing Flow (Source: Data Processing, 2025)

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3. RESULTS AND DISCUSSION

Changes in Mangrove Cover Area and Density Levels in Deli Serdang Regency

Understanding spatial and temporal changes in mangrove ecosystems requires a clear visualization of distribution patterns and density levels over time. Remote sensing-based mapping provides an effective way to capture these dynamics, particularly when comparing multi-year datasets. In this study, satellite imagery was used to generate thematic maps illustrating the spatial distribution of mangrove density classes in 2020 and 2024. To begin with, the spatial distribution of mangrove density in 2020 is presented to establish the baseline condition of the ecosystem prior to recent changes.

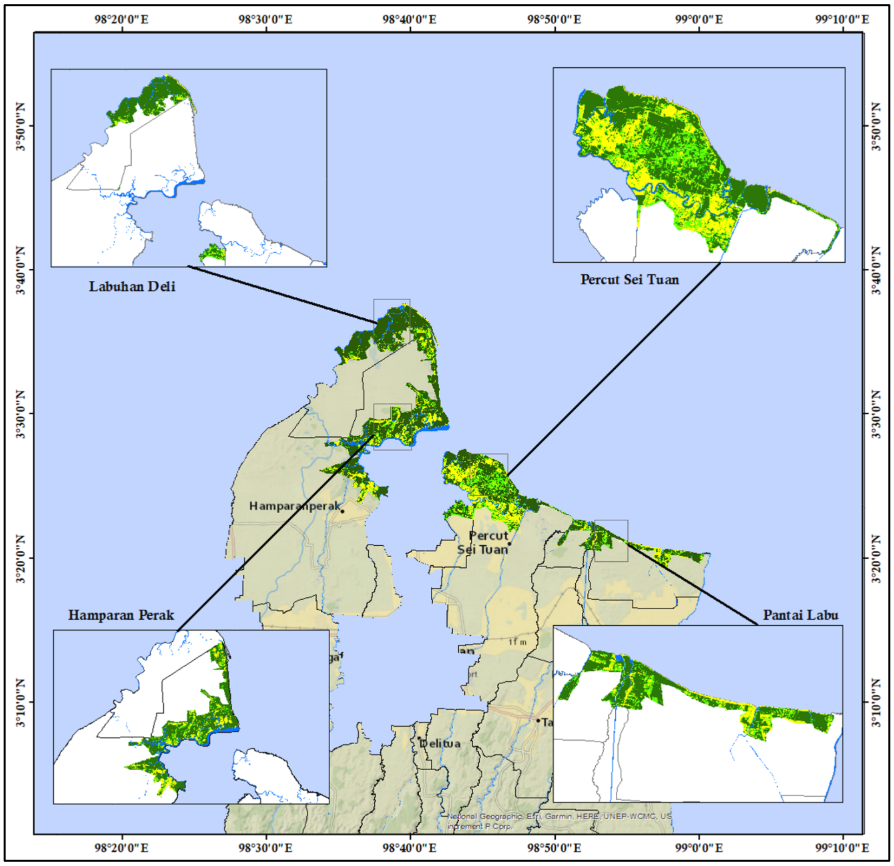

Figure 2. Mangrove Density Map in 2020 (Source: Data Processing, 2025)

The map above shows that dense mangrove areas were still dominant in several coastal zones, particularly in Hamparan Perak and Percut Sei Tuan. Moderate and sparse classes were distributed more heterogeneously, indicating variation in environmental conditions and disturbance levels across the region. To better understand the spatial distribution shown in Figure 2, the following table presents a quantitative breakdown of mangrove density across sub-districts in 2020.

Table 1. Mangrove Density Distribution in 2020

Sub-district	Density Class (ha)			Total (ha)	Percentage
	Dense	Moderate	Sparse		
Hamparan Perak	3.096	595	1.243	4.934	36%
Labuhan Deli	2.272	275	387	2.934	21%
Pantai Labu	956	285	338	1.579	12%
Percut Sei Tuan	2.029	923	1.295	4.247	31%
Total	8.353	2.078	3.263	13.694	100%

(Source: Data Processing, 2025)

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The tabulated data confirm that dense mangrove vegetation dominated the study area in 2020, accounting for more than half of the total coverage. Hamparan Perak contributed the largest share, followed by Percut Sei Tuan, indicating that these areas functioned as core zones of mangrove ecosystems at that time. Subsequently, the spatial distribution of mangrove density in 2024 is presented to highlight changes over the four-year period.

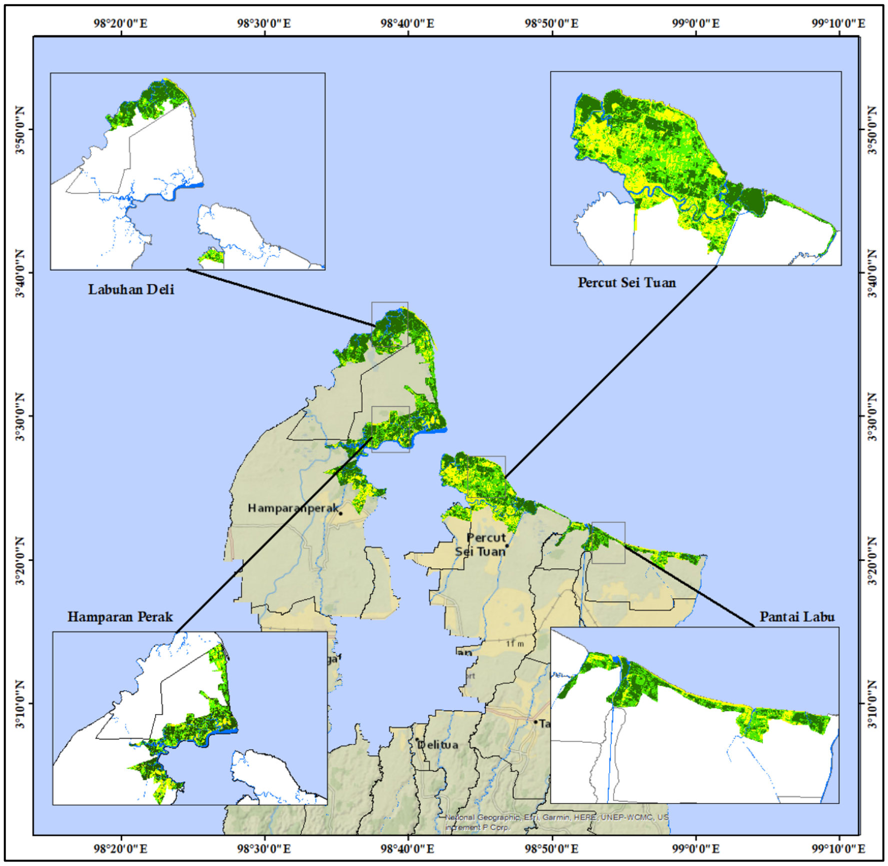

Figure 3. Mangrove Density Map in 2024 (Source: Data Processing, 2025)

The 2024 map reveals a noticeable reduction in dense mangrove areas, accompanied by an expansion of moderately dense vegetation. This visual shift suggests a transformation in vegetation structure rather than a complete loss of mangrove cover, indicating gradual ecological degradation. To complement the spatial interpretation of Figure 3, the following table provides a detailed quantitative comparison of mangrove density distribution in 2024.

Table 2. Mangrove Density Distribution in 2024

Sub-district	Density Class (ha)			Total (ha)	Percentage
	Dense	Moderate	Sparse		
Hamparan Perak	2.068	1.494	1.252	4.814	36%
Labuhan Deli	1.632	775	460	2.867	22%
Pantai Labu	570	534	288	1.392	11%
Percut Sei Tuan	1.293	1.458	1.349	4.100	31%
Total	5.563	4.261	3.349	13.173	100%

(Source: Data Processing, 2025)

The data presented in Table 2 indicate a substantial decline in dense mangrove areas alongside a significant increase in moderate-density classes. Although the total area reduction is relatively moderate, the internal shift in density composition highlights a more critical ecological transformation. The comparison

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between 2020 and 2024 demonstrates that mangrove ecosystems in Deli Serdang Regency are undergoing structural changes, characterized by a shift from dense vegetation to moderate-density vegetation. This pattern reflects a gradual degradation process in which the ecological quality of mangroves declines before a significant reduction in total area becomes evident. Such changes are often associated with disturbances that reduce canopy cover, alter species composition, and weaken ecosystem resilience.

Similar findings have been reported in recent studies across Indonesia and Southeast Asia. Previous research indicates that mangrove degradation frequently manifests as a shift from dense to moderate density due to increasing anthropogenic pressure, including aquaculture expansion, coastal development, and land-use conversion. Studies Yusiyanti et al. (2025) in Teluk Semanting and Hanum et al. (2026) in Aceh Tamiang, for example, highlight that even when total mangrove area remains relatively stable, internal structural changes can signal the early stages of ecosystem decline. This reinforces the importance of density-based analysis as a more sensitive indicator of mangrove health.

From a spatial perspective, Hamparan Perak remains the largest contributor to mangrove coverage, suggesting its continued ecological importance within the region. However, the reduction in dense vegetation within this sub-district indicates that even core areas are not immune to environmental pressure. Meanwhile, Pantai Labu consistently shows the lowest coverage and density levels, reflecting higher vulnerability and possibly greater exposure to human activities. This spatial variation aligns with Jia et al. (2023) findings that emphasize the role of accessibility, population pressure, and land-use intensity in shaping mangrove distribution patterns.

Environmental and anthropogenic factors jointly influence these observed changes. Yunita et al. (2025) confirms that mangrove ecosystems are highly sensitive to both natural conditions, such as sedimentation and water quality, and human-induced disturbances. The expansion of moderate-density areas in this study likely reflects a combination of ecological stressors that reduce vegetation vigor without immediately eliminating mangrove presence. Over time, if such pressures persist, these areas may transition further into sparse vegetation or be completely lost. The integration of spatial mapping and quantitative analysis reveals that mangrove changes in Deli Serdang Regency are characterized by a reduction in total area and significant shifts in vegetation structure. These findings highlight the need for continuous monitoring using remote sensing technologies and the implementation of adaptive management strategies to prevent further degradation and ensure the long-term sustainability of mangrove ecosystems.

Accuracy of Mangrove Mapping Using Sentinel-2A and Normalized Difference Vegetation Index

In this study, the accuracy of mangrove density classification was evaluated using ground truth data obtained through field surveys. The validation process involved comparing classified satellite imagery with observed conditions at selected sample points using a confusion matrix approach. To provide a clear overview of classification performance, the following table presents the accuracy assessment results, including overall accuracy and the Kappa coefficient.

Table 3. Accuracy Assessment of Mangrove Classification

Classification Category	Reference Data	Classified Data	Correct Classification	Accuracy (%)
Dense	30	28	26	86.7%
Moderate	25	27	21	84.0%
Sparse	20	18	16	80.0%
Total / Overall Accuracy	75	73	63	83.0%
Kappa Coefficient				0.76

(Source: Data Processing, 2025)

The results in Table 3 indicate that the overall classification accuracy reached 83%, with a Kappa coefficient of 0.76. These values suggest a strong level of agreement between the classified image and field observations. An overall accuracy above 80% and a Kappa value above 0.70 are generally considered acceptable and indicate reliable classification performance. The slightly lower accuracy in the sparse category may be attributed to spectral similarity between sparse mangroves and other coastal vegetation or bare land, complicating classification.

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The findings of this study are consistent with previous research utilizing Sentinel-2A imagery and vegetation indices. Research by Faizal et al. (2023) in Makassar demonstrated that NDVI transformation applied to Sentinel-2A imagery is effective in mapping mangrove conditions, with clear differentiation of vegetation density classes and reliable classification performance. The study confirmed that NDVI values can accurately represent mangrove canopy density and are suitable for spatial monitoring of coastal vegetation dynamics.

Similarly, research by Simarmata et al. (2021) in the eastern coastal region of Lampung (2021) showed that NDVI-based classification provides reliable results for identifying mangrove density, with accuracy levels considered acceptable for ecological analysis. The study also highlighted that NDVI is one of the most widely used indices due to its simplicity and effectiveness, although it may face limitations when distinguishing mangroves from other vegetation types with similar spectral characteristics. Research indicates that Sentinel-2-based NDVI classification is effective for vegetation mapping, although classification accuracy may vary with environmental complexity and spectral similarity among land cover types. The study emphasized that integrating satellite imagery with field validation significantly improves classification accuracy, particularly in heterogeneous coastal ecosystems such as mangroves.

In addition to methodological factors, field validation plays a critical role in ensuring accuracy. In this study, purposive sampling was used to capture variation in mangrove density across locations, thereby improving the representativeness of the validation data. The use of GPS during field surveys further enhanced positional accuracy, minimizing spatial discrepancies between ground observations and satellite imagery. This approach aligns with best practices in remote sensing studies, where combining image classification with field verification is essential for producing high-quality spatial data. The accuracy assessment confirms that the use of Sentinel-2A imagery and the Normalized Difference Vegetation Index method provides a reliable and efficient approach for mapping mangrove density. The relatively high accuracy achieved in this study supports its application for long-term monitoring and decision-making in coastal ecosystem management, particularly in regions experiencing dynamic environmental changes.

Factors Influencing Mangrove Density in Deli Serdang Regency

Mangrove density is influenced by a complex interaction between environmental conditions and anthropogenic pressures that shape vegetation structure, spatial distribution, and long-term ecosystem stability. The results of this study indicate a clear shift from dense to moderate mangrove classes, suggesting a gradual degradation process rather than immediate deforestation. This transformation reflects a decline in canopy cover and biomass, which often occurs as an early response to ecological stress. In many coastal regions, such structural changes precede large-scale loss of mangrove area, making density an important indicator of ecosystem health. Similar patterns have been documented in several regions of Indonesia, where mangrove degradation is not always reflected in total area reduction but rather in a decline in vegetation density due to ongoing environmental and human pressures.

Water quality, particularly pH conditions, plays a crucial role in determining mangrove growth and density. The pH range identified in this study (5.85–7.12) falls within the optimal threshold for mangrove development, supporting nutrient availability and root function. Stable pH conditions enable efficient nutrient absorption and physiological processes, allowing mangroves to maintain dense canopies. Research conducted by Sari & Soeprobowati (2021) confirms that water quality parameters, including pH, salinity, and dissolved oxygen, significantly influence mangrove density and productivity in coastal ecosystems. Their findings indicate that fluctuations in water chemistry can reduce growth rates and lead to less dense vegetation structures, especially in areas experiencing environmental disturbance.

In addition to water quality, substrate characteristics are a fundamental factor influencing mangrove density. The dominance of muddy substrates in dense mangrove areas observed in this study highlights the importance of sediment composition in supporting vegetation growth. Muddy substrates provide greater nutrient retention, better moisture availability, and stronger root anchorage than sandy substrates, which tend to be less stable and nutrient-poor. This finding is consistent with research conducted by Simarmata et al. (2021) in the eastern coastal region of Lampung (2021), which demonstrated that mangrove density is significantly higher in areas with fine-grained sediments due to improved ecological conditions for root development and nutrient uptake. These results emphasize that substrate quality directly affects mangrove presence and the structural integrity and density of the ecosystem.

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Anthropogenic activities are among the dominant drivers of changes in mangrove density in Indonesia. In the study area, the reduction of dense mangrove classes is closely associated with land conversion for aquaculture, settlements, and coastal infrastructure development. Such activities alter the natural landscape, disrupt hydrological patterns, and reduce the ecological capacity of mangrove ecosystems. A study Muryani et al. (2026) conducted in Demak, Central Java (2022) found that the expansion of aquaculture ponds significantly reduced mangrove density and fragmented existing vegetation, leading to long-term ecological degradation. These findings highlight that human-induced land-use change reduces mangrove area and weakens vegetation structure, making ecosystems more vulnerable to further disturbance.

Spatial accessibility and proximity to human settlements further influence mangrove density distribution. Areas that are easily accessible, such as those located near roads, rivers, and urban centers, tend to experience higher levels of disturbance due to increased human activities. This results in lower vegetation density and greater ecosystem fragmentation. Research Hanum et al. (2026) conducted in Riau supports this observation, indicating that mangrove areas located near residential and industrial zones show higher degradation levels compared to more remote locations. The study emphasizes that accessibility is a critical factor in determining the intensity of human pressure on mangrove ecosystems, as it facilitates land exploitation and increases the likelihood of environmental degradation.

Furthermore, the interaction between environmental and anthropogenic factors determines the overall dynamics of mangrove ecosystems. Mangrove degradation is rarely caused by a single factor; instead, it results from the cumulative effects of environmental stressors and human interventions. Pratiwi (2025) highlights that changes in mangrove ecosystems in Indonesia are driven by the combined influence of land-use change, environmental conditions, and socio-economic activities. The study emphasizes that effective mangrove management requires an integrated approach that considers both ecological and human dimensions. Without proper management, the ongoing transition from dense to moderate mangrove classes observed in this study may continue, eventually leading to further degradation and potential loss of mangrove ecosystems in Deli Serdang Regency.

4. CONCLUSION

This study demonstrates that mangrove ecosystems in Deli Serdang Regency have experienced a decline in total coverage alongside a significant shift in vegetation structure, particularly from dense to moderate density classes between 2020 and 2024. The use of Sentinel-2A imagery and the Normalized Difference Vegetation Index method proved effective in mapping and monitoring these changes, with an overall accuracy of 83% and a Kappa coefficient of 0.76, indicating reliable classification results. The findings reveal that mangrove degradation is influenced by both environmental factors, such as water pH and substrate type, and anthropogenic pressures, including land conversion and increasing accessibility. The observed transition in density highlights early-stage ecological degradation, emphasizing that structural changes in mangrove vegetation can serve as critical indicators of ecosystem health before substantial area loss occurs.

Based on these findings, it is recommended that sustainable mangrove management in Deli Serdang Regency be strengthened through integrated approaches that combine continuous monitoring, environmental management, and community-based conservation. The application of remote sensing technologies, particularly Sentinel-2A and Normalized Difference Vegetation Index, should be maintained and expanded for periodic evaluation of mangrove conditions. In addition, stricter regulation of land-use conversion, especially in coastal areas, is necessary to reduce anthropogenic pressure on mangrove ecosystems. Restoration efforts should prioritize degraded areas with moderate density to prevent further decline, while environmental factors such as water quality and substrate conditions must be managed to support optimal mangrove growth. Collaborative involvement among government, local communities, and stakeholders is essential to ensure long-term conservation and sustainability of mangrove ecosystems.

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