Mangrove Ecosystem Vulnerability through Integrated Remote Sensing: A Systematic Literature Review

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Abstract. Mangrove ecosystems play a crucial role in maintaining the stability of coastal environments, but they face various pressures due to human activities and environmental changes that increase their vulnerability. This research aims to examine the development of remote sensing-based approaches in monitoring the condition, changes, and vulnerability of mangrove ecosystems, as well as to identify the main factors affecting their degradation. The method used is a Systematic Literature Review (SLR) with qualitative descriptive analysis of scientific publications related to mangrove monitoring using remote sensing technology. The study results show that remote sensing-based mangrove research has significantly increased, especially after 2010, along with the development of sensor technology, geographic information systems (GIS), and artificial intelligence methods. The main factors affecting the vulnerability of mangroves include anthropogenic pressures such as land conversion and pollution, environmental factors such as rising sea levels and hydrological changes, as well as biophysical factors related to the structure and condition of the vegetation. The integration of remote sensing, GIS, and spatial analysis has proven to enhance the effectiveness of monitoring and understanding the dynamics of mangrove ecosystem changes. Thus, an integrated geospatial approach becomes an important foundation in supporting the sustainable management and conservation of mangroves.

Keywords: mangrove, ecosystem vulnerability, remote sensing, geographic information system, mangrove monitoring.

I. INTRODUCTION

Mangrove ecosystems are one of the coastal ecosystems that play a very important ecological role in maintaining the stability of coastal and marine environments. The presence of mangroves serves as a natural protector of the coast from abrasion, waves, and storms that frequently occur in coastal areas [1][2]. In addition, this ecosystem also provides important habitats for various marine and terrestrial organisms that utilize coastal areas for breeding, foraging, and sheltering [3]. Mangroves are also known as one of the ecosystems with high carbon storage capacity, thus significantly contributing to global climate change mitigation [4]. However, various studies show that the condition of mangrove ecosystems in different parts of the world is experiencing significant pressure due to human activities and environmental changes [5][6]. These pressures include coastal land conversion, environmental pollution, hydrological changes, and sea level rise related to climate change [7]. This condition increases the vulnerability of mangrove ecosystems to ecological damage and changes in the structure of coastal ecosystems. Therefore, continuous monitoring of mangrove conditions becomes very important to understand the dynamics of changes occurring and to effectively support coastal ecosystem conservation efforts [8][9].

Pressure on mangrove ecosystems does not only come from natural environmental factors but is also significantly influenced by human activities in coastal areas. One form of anthropogenic pressure that is often found is the accumulation of marine debris, particularly plastic waste, which gets trapped in mangrove vegetation. Research conducted by [10] shows that plastic waste accumulated on mangrove roots can disrupt the growth of vegetation and hinder the gas exchange process in mangrove aerial roots. These conditions not only affect the health of mangrove vegetation but can also disrupt the habitat structure for organisms living within that ecosystem. In addition to environmental pollution, coastal development activities also exert significant pressure on the sustainability of mangrove ecosystems. Changes in coastal land use for the purposes of infrastructure development, industry, and other economic activities often lead to the degradation of mangrove ecosystems. In this context, various studies show that human activities are one of the main factors increasing the vulnerability of mangrove ecosystems. Therefore, understanding the interaction between anthropogenic pressures and environmental conditions becomes very important in the analysis of mangrove vulnerability.

Beside anthropogenic pressure, climate change is also one of the important factors affecting the stability of mangrove ecosystems in various coastal areas. Research conducted by [11] shows that mangrove ecosystems have a high level of vulnerability to climate change, particularly related to sea level rise and changes in coastal hydrology. Mangrove areas at low elevations have a higher risk of degradation because they are vulnerable to inundation and changes in environmental conditions. Moreover, coastal development can also hinder the natural adaptive capacity of mangroves to environmental changes. This shows that the vulnerability of mangroves is the result of a complex interaction between environmental factors and human activities. Therefore, the analysis of mangrove ecosystem vulnerability requires a multidimensional approach that simultaneously considers various ecological, hydrological, and anthropogenic factors. A comprehensive approach is essential to understand the dynamics of changes occurring in the mangrove ecosystem. Thus, research on mangrove vulnerability plays an important role in supporting sustainable coastal management strategies.

In recent decades, remote sensing technology has rapidly developed and become one of the main methods in coastal ecosystem research. This technology allows for the observation of environmental conditions on a large scale with greater efficiency compared to conventional field survey methods. Remote sensing technology provides significant opportunities to monitor the distribution and changes of mangrove ecosystems globally thru the use of multi-temporal satellite imagery [8]. Satellite image data such as Landsat and various other sensors enable the analysis of mangrove cover changes over several decades. This provides an advantage in understanding the dynamics of mangrove changes over time and identifying trends in ecosystem degradation. In addition, remote sensing technology also allows for integration with various image analysis methods such as land cover classification and vegetation index analysis. Thus, this technology becomes a very important tool in the sustainable monitoring of mangrove ecosystems.

The development of remote sensing methodologies also increasingly enriches the approach to analyzing the condition of mangrove ecosystems. Explain that mangrove monitoring can be conducted thru a combination of various types of remote sensing data such as multispectral images, radar, and LiDAR. Multispectral images allow for the analysis of spectral characteristics of vegetation related to the health and density of mangroves. Meanwhile, radar and LiDAR technology provide information on the vertical structure of vegetation such as canopy height and mangrove forest density. The combination of these various data sources enables a more comprehensive analysis of the biophysical conditions of mangroves. In addition, the use of vegetation indices such as the Normalized Difference Vegetation Index (NDVI) is also often employed to evaluate the health condition of mangrove vegetation. Thus, the remote sensing approach provides various analytical methods capable of depicting the condition of mangrove ecosystems in greater detail. This shows that remote sensing technology has great potential in supporting coastal ecosystem research.

In addition to the development of remote sensing technology, the integration of remote sensing and geographic information systems (GIS) has also become an important approach in the analysis of mangrove ecosystems. Showed that GIS-based spatial analysis can be used to evaluate the vulnerability levels of mangroves by integrating various environmental indicators such as coastal geomorphology, shoreline changes, and human activity pressures. This approach allows for the identification of mangrove areas that have a high level of vulnerability to environmental changes. Other research also shows that multi-temporal spatial analysis can be used to monitor changes in mangrove distribution in the long term [12]. Meanwhile, the integration of satellite imagery data and GIS allows for a more accurate analysis of changes in mangrove cover over spatial and temporal scales [13]. Furthermore, research conducted by [14] shows that changes in mangrove distribution can also be influenced by rising sea levels, causing mangroves to migrate inland. Another study also emphasizes that changes in mangrove distribution can be an important indicator in understanding the vulnerability of coastal ecosystems [15]. Thus, the integration of geospatial technology makes a significant contribution to enhancing the effectiveness of mangrove ecosystem monitoring.

Although various studies have shown significant progress in the use of geospatial technology for monitoring mangroves, there are still several research gaps that need to be further examined. Most previous studies have still focused on mapping mangrove distribution or analyzing changes in land cover area. Studies that specifically analyze the vulnerability levels of mangrove ecosystems thru an integrative approach based on remote sensing are still relatively limited. In addition, some studies predominantly use regional or global scale approaches, which provide less in-depth understanding of the dynamics of mangrove vulnerability at a more detailed spatial scale. Other studies also show that mangrove vulnerability analysis needs to consider the interaction between environmental, social, and human activity factors simultaneously [16]. Therefore, research that integrates various spatial analysis approaches and remote sensing technology becomes very important to provide a more comprehensive understanding of the dynamics of mangrove ecosystem degradation [13]. This integrative approach is expected to provide scientific contributions in the development of geospatial technology-based mangrove monitoring methods.

Based on this background, this research aims to examine an integrative approach based on remote sensing in identifying the vulnerability and dynamics of mangrove ecosystem damage spatially. This study seeks to review the development of methodological approaches in utilizing remote sensing technology to monitor the condition, changes, and vulnerability of mangrove ecosystems based on published scientific literature. Additionally, this research also aims to identify environmental, anthropogenic, and biophysical factors that are most frequently identified in the literature as determinants of the vulnerability levels of mangrove ecosystems. This study will also analyze how these factors are integrated into spatial data and remote sensing-based research. Furthermore, this research aims to evaluate the contribution of integrating remote sensing, geographic information systems, and spatial analysis in enhancing the effectiveness of mangrove ecosystem monitoring. Thus, this study is expected to provide a more comprehensive understanding of the dynamics of mangrove ecosystem changes.

II. METHODOLOGY

This research uses a systematic literature review (SLR) design with a qualitative-descriptive analysis orientation combined with mapping publication trends and thematic synthesis of research findings on monitoring the vulnerability or damage of mangrove ecosystems based on remote sensing. The selection of this design is based on the research objectives that do not focus on the collection of primary field data, but rather on the systematic tracing, selection, evaluation, and synthesis of relevant scientific articles with three research problem formulations, namely the methodological development of remote sensing, the determining factors of mangrove vulnerability, and the contribution of integrating remote sensing, GIS, and spatial analysis. The SLR design was chosen because it meets the need to systematically examine how scientific literature builds understanding of the monitoring of conditions, changes, and vulnerabilities of mangroves, while also placing this research in a previously identified gap in the literature. In the synthesis narrative, it is emphasized that previous studies tend to still focus on mapping the distribution and changes in mangrove cover, whereas studies that specifically monitor the level of vulnerability or damage to mangrove ecosystems in an integrated manner using remote sensing are still relatively limited. These findings serve as the conceptual basis for the design of this research method, so the literature review process is specifically directed to capture the development of integrative approaches rather than merely inventorying conventional mangrove mapping studies. This research also places literature as the main subject of analysis, so the unit of analysis is not individuals or field locations, but rather scientific documents selected thru a process of identification, screening, and feasibility assessment. Substantively, this approach aligns with the need to understand how previous research has utilized multi-temporal satellite imagery, vegetation indices, image classification, radar, LiDAR, GIS, spatial analysis, and modeling in mangrove studies, as illustrated in the literature synthesis highlighting the roles of [8][17][12], and [13]. Thus, the design of this research is structured to produce a systematic, traceable synthesis that can comprehensively answer research questions based on the available literature.

The characteristics of the sample or subjects in this study are scientific articles obtained thru searches on Publish or Perish with the source Google Scholar. Based on the State-of-the-art POP data access, the search began with monitoring mangroves, machine learning, deep learning, and similar themes. Then, it resulted in 859 identified publications. Next, 8 publications from 2026 were removed from the initial set to ensure the analysis remained consistent within the specified year range, resulting in a total of 851 articles after the initial screening. The set of 851 publications was then categorized into several topic groups: remote sensing with 382 articles, health with 202 articles, approach/evaluation/experiment/others with 113 articles, ecology with 44 articles, social with 28 articles, machine learning with 27 articles, IoT with 18 articles, deep learning with 16 articles, review with 14 articles, and environment with 7 articles. An initial screening was then conducted by removing articles marked as not meeting the criteria by the automated tool within the 2010–2025 range, totaling 4 records, articles removed for other reasons related to journal tier, totaling 5 records, without any duplicates or articles without abstracts as shown in figure 1.

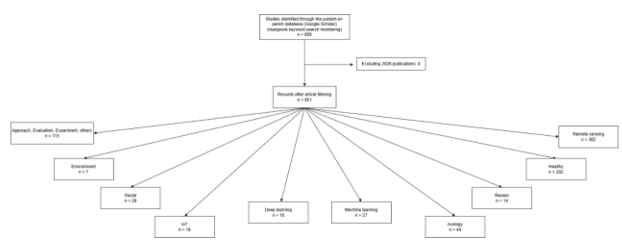

Figure 1. State-of-the-art POP data access.

The characteristics of the publications analyzed thru Publish or Perish are determined based on inclusion and exclusion criteria explicitly formulated so that the literature selection process can be replicated by other researchers. Inclusion criteria include articles that discuss monitoring, mapping, classification, change detection, biomass, distribution, or the condition of mangroves using remote sensing technology, such as satellite imagery, UAV imagery, radar data, multispectral data, and multi-source data analyzed using machine learning, deep learning, or other relevant artificial intelligence approaches. Based on these criteria, the eligible publications are then analyzed to identify the development of research over time.

In the analysis stage, the collected studies were then organized based on the development of their methodological approaches. Initially, the use of multi-temporal satellite imagery was employed to monitor changes in mangrove distribution, which then evolved into a more complex approach thru the combination of multispectral images, radar, LiDAR, the use of vegetation indices, and increasingly sophisticated classification techniques as explained by [8] and [17]. This development indicates a shift from descriptive monitoring methods to more integrative analyzes based on multi-source data. Next, these studies were compared to identify various factors most frequently mentioned as determinants of mangrove ecosystem vulnerability. These factors include anthropogenic pressures such as the presence of plastic waste highlighted by [10], hydrological changes and sea level rise discussed by [11], as well as geomorphological aspects and coastal change dynamics as explained. Additionally, several studies also highlight the shift in mangrove distribution as a response to climate change, as revealed by [14] and [15], which further underscores the complexity of the factors affecting the sustainability of this ecosystem. On the other hand, attention is also given to how the integration of various approaches can enhance monitoring effectiveness while deepening the understanding of mangrove dynamics. Various studies show that the combination of remote sensing, GIS, spatial analysis, and modeling yields more comprehensive results, even when integrated with socio-ecological approaches. This is evident from the use of techniques such as image classification, landscape indices, clustering, multi-scale approaches, and the integration of stakeholder perspectives as described by [12][13] and [16].

Publication trend analysis shows that interest in the use of remote sensing for mangrove monitoring continues to increase, especially with the advancement of sensor technology and artificial intelligence methods. The increase in the number of publications reflects the growing attention of the scientific community toward the management and conservation of mangrove ecosystems supported by geospatial technology. Thru the Systematic Literature Review (SLR) approach, this research not only summarizes previous research findings but also interprets the relationships between findings, identifies patterns in the development of research topics, and reveals research gaps that are still open for further investigation. Thus, the analysis results can provide a more comprehensive picture of the direction of remote sensing-based mangrove research development. Additionally, the research method used can be clearly replicated by other researchers as it follows systematic stages, namely identification, selection, extraction, categorization, and literature synthesis.

III. RESULT AND DISCUSSION

3.1 Systematic literature review

The synthesis results were obtained from a systematic literature review process conducted on scientific articles relevant to the topic of monitoring the vulnerability or damage levels of mangrove ecosystems thru remote sensing analysis [1][18][9]. The literature identification process yielded a number of articles, which were then selected using the PRISMA stages, resulting in studies that met the research inclusion criteria [19]. The selected studies come from various coastal regions of the world with diverse focuses, including the vulnerability of mangroves to human activities, climate change, coastal environmental dynamics, and the use of remote sensing technology in monitoring mangrove ecosystems [20][5][21]. The data collected from each article include the research objectives, methods used, types of remote sensing data, and key findings related to the condition and dynamics of mangrove ecosystems [22][23]. The information was then synthesized to identify research patterns, methodological approaches, and factors influencing the vulnerability of mangrove ecosystems [24].

In addition, synthesis was also conducted to illustrate the integration of remote sensing technology, geographic information systems (GIS), and spatial analysis in published research [25][26]. The synthesis results show that studies on mangrove vulnerability have rapidly developed over the past few decades in line with advancements in geospatial technology and the increased availability of satellite imagery data [27]. The analyzed research also reveals variations in methodological approaches to monitoring mangrove ecosystems in various coastal regions.

3.2 Trends in research publication

The results of the literature search indicate that publications related to the use of remote sensing, machine learning, and artificial intelligence for mangrove monitoring have shown a significant increasing trend during the period 1978–2025. Based on figure 2, the first publication was identified in 1978, but the number of studies during the 1978–2000 period was still relatively low, with the number of publications generally not exceeding seven articles per year. This condition indicates that remote sensing-based mangrove monitoring studies are still in the early stages of development and have not yet received much attention from the scientific community.

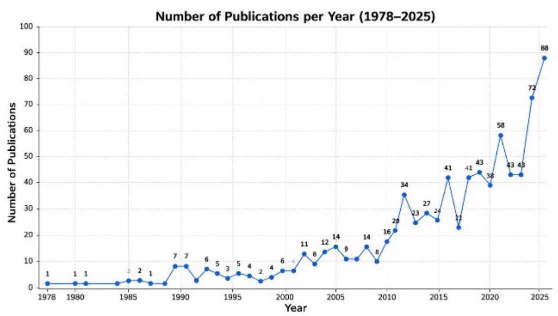

Figure 2. Publication graph monitoring the level of vulnerability or damage to mangrove ecosystem thru remote sensing analysis.

The increase in the number of publications began to be noticeable after the year 2000, along with the development of remote sensing technology, the increasing availability of satellite imagery, and the enhanced computational capabilities for processing spatial data. This upward trend became even more apparent after 2010, marked by the growing number of studies utilizing various remote sensing data sources for mapping, classification, change detection, biomass estimation, and monitoring the condition of mangrove ecosystems. A more significant surge in publications occurred during the period 2018–2025. During this timeframe, the number of publications consistently increased and peaked in 2025 with 88 publications, after previously reaching 72 publications in 2024.

The sharp increase indicates the growing interest of researchers in utilizing remote sensing technology combined with machine learning and deep learning methods to support more accurate and efficient mangrove monitoring. Moreover, the trend of increasing publications also reflects the growing global attention toward the importance of mangrove ecosystems in climate change mitigation, coastal area protection, biodiversity conservation, and sustainable coastal resource management. The dominance of publications in the last decade indicates that remote sensing-based mangrove monitoring is one of the actively developing research fields and has great prospects for continued study in the future.

3.3 Keyword visualization (vosviewer)

Keyword network analysis was conducted using VOSviewer software version 1.6.20. The visualization in figure 3 shows the relationships between keywords based on their co-occurrence frequency in the analyzed research documents. Each node in the graph represents a keyword, while the size of the node indicates the frequency of occurrence of that keyword. In addition, different colors indicate groups or clusters of related research topics, while connecting lines show the relationships or connections between keywords.

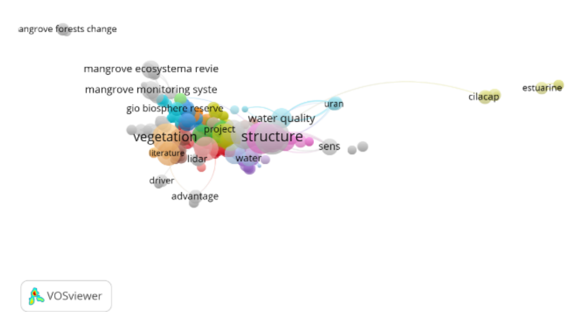

Figure 3. Network visualization monitoring mangrove

Based on the visualization, it is evident that the keywords "structure" and "vegetation" have relatively larger node sizes compared to other keywords, indicating that these two terms are the most frequently appearing topics in mangrove monitoring research. These two keywords are also positioned centrally in the network, signifying that they are interconnected with many other keywords. Additionally, there are several other keywords that also stand out, such as "water quality," "lidar," and "project," indicating that mangrove monitoring research does not only focus on vegetation aspects but also involves environmental factors such as water quality and the use of remote sensing technology. The keyword "water quality" has a direct relationship with the main keywords, indicating that the quality of aquatic environments is an important aspect in mangrove studies. Meanwhile, the appearance of the keyword "lidar" indicates the use of active sensor-based mapping technology in some studies. On the other hand, there are several keywords that are positioned further away from the main cluster, such as "cilacap" and "estuarine," indicating that research on these topics is more specific or case studies in certain areas. The position of these separate keywords indicates that the research is not closely related to the main topic in the network. In addition, there are also keywords such as "mangrove monitoring system," "biosphere reserve," and "ecosystem review" that form their own cluster, indicating the presence of research groups focusing on monitoring systems and the general study of mangrove ecosystems.

Meanwhile, the overlay visualization results depict the temporal development of the research based on the year of publication, as shown thru the color gradient on each node in figure 4. The blue color indicates keywords that appeared in the early period of the research, while the green to yellow colors indicate keywords that appeared in the more recent period.

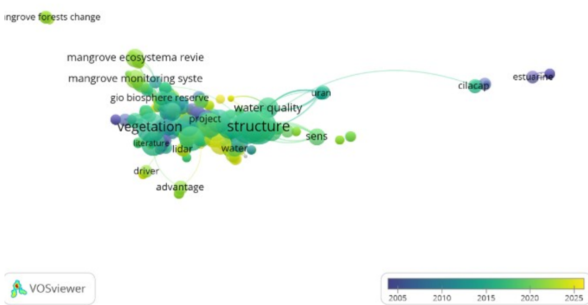

Figure 4. Overlay visualization monitoring mangrove

Based on the image, it can be seen that keywords such as "estuarine" and "cilacap" tend to have a blue to dark blue color, indicating that these topics appeared more frequently in the early periods of research. This indicates that early research in the field of mangrove monitoring was more focused on case studies of specific regions or environmental conditions. In addition, several other keywords that also appear in the early phase tend to be related to conventional approaches in remote sensing. Next, in the mid-development phase, indicated by the green color, keywords such as "vegetation," "structure," and "water quality" begin to appear. This shows that the research is starting to shift toward the analysis of mangrove vegetation structure and its relationship with environmental factors such as water quality. At this phase, the focus of the research begins to shift from descriptive studies to a more in-depth analysis of the characteristics of the mangrove ecosystem. Additionally, the emergence of keywords such as "lidar" and "project" indicates the use of more advanced remote sensing technology to support this analysis. In the latest phase, indicated by the yellow color, there is an increase in keywords such as "mangrove monitoring system," "ecosystem review," as well as several terms related to more complex systems and analytical approaches. Overall, the results of this overlay visualization indicate that mangrove monitoring research has undergone dynamic development over time. The initial research focused more on site studies and environmental conditions, then evolved into the analysis of structure and vegetation, and finally progressed toward the development of more complex and integrated monitoring systems.

3.4 Factors causing the vulnerability of mangrove Ecosystems

The synthesis results show that the vulnerability of mangrove ecosystems is influenced by various factors, both anthropogenic and environmental, as depicted in figure 5.

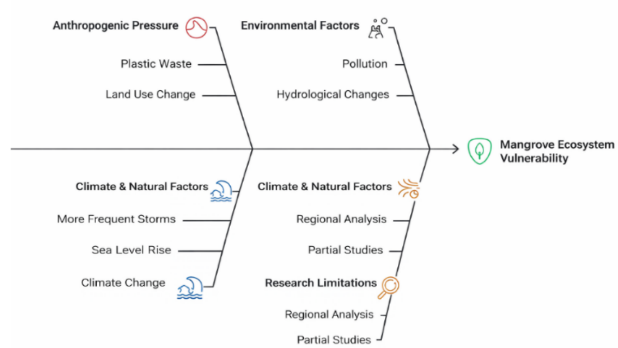

Figure 5. Pressure on the Mangrove Ecosystem

One of the main factors that is often identified is the accumulation of marine debris, particularly plastic. Research by [10] shows that plastic waste trapped in mangrove roots can disrupt vegetation growth and gas exchange processes. Additionally, waste also affects the habitat structure of organisms living within the mangrove ecosystem. Another significant factor is climate change and coastal environmental dynamics. [11] showed that rising sea levels and hydrological changes increase the vulnerability of mangroves, especially in low-elevation areas. Changes in hydrological conditions also affect the distribution and health of vegetation. Furthermore, coastal geomorphological factors also play an important role. That coastal erosion and changes in the shoreline can increase the risk of mangrove damage. Areas with high erosion rates tend to have greater vulnerability to environmental degradation. Research by [14] also shows that rising sea levels can cause mangrove migration inland. However, this process is influenced by topographic conditions and spatial limitations due to human activities. This shows that the vulnerability of mangroves is the result of a complex interaction between environmental factors and anthropogenic pressures.

3.5 Integration of approaches in mangrove monitoring

The synthesis results also indicate that the integration of various approaches is key to enhancing the effectiveness of mangrove ecosystem monitoring as shown in table 1.

TABLE 1. SYNTHESIS OF SIGNIFICANT FACTORS AFFECTING MANGROVE ECOSYSTEMS ACROSS DIFFERENT GEOGRAPHIC CONTEXTS

Ref.	Geographic Context	Significant Factors Identified	Catagory
[8]	Global mangrove ecosystems	Mangrove distribution change, land-cover dynamics, long-term vegetation change	Biophysical

[10]	Coastal mangrove ecosystems affected by marine debris	Plastic waste accumulation, anthropogenic pressure	Anthropogenic
[12]	Long-term mangrove monitoring region	Land-use conversion, environmental management policies, landscape fragmentation	Anthropogenic / Environmental
[13]	Decadal mangrove monitoring area	Vegetation dynamics, land-cover change, canopy condition	Biophysical
[17]	Mangrove forests assessed using LiDAR and radar data	Forest structure, canopy height, vegetation density, biomass condition	Biophysical

Research by [12] shows that the use of multi-temporal satellite imagery over the long term can more comprehensively depict the dynamics of mangrove changes. In the study, changes in mangrove area were influenced by human activities such as land conversion, as well as environmental management policies. Furthermore, the use of landscape indices and clustering analysis allows for the identification of spatial change patterns in greater detail. The integration of remote sensing, GIS, and spatial analysis allows for a deeper understanding of the dynamics of mangrove ecosystems. This approach not only improves mapping accuracy but also helps in identifying the factors causing changes and formulating more effective management strategies. The synthesis results show that an integrative approach using multiple data sources significantly contributes to understanding the complexity of mangrove ecosystems and supports coastal conservation and management efforts.

The analyzed literature shows that the pressures on mangroves are present in various forms, ranging from the accumulation of plastic waste, land use changes, pollution, hydrological changes, sea level rise, coastal erosion, to barriers to land migration. At the same time, remote sensing technology, GIS, and spatial analysis serve as the main tools that enable these various pressures to be identified, mapped, and tracked temporally. Thus, the findings of this study affirm that modern mangrove monitoring is shifting from a static inventory approach to an integrative approach that assesses the dynamics of damage and vulnerability in spatial and temporal dimensions.

The development of methodological approaches in the utilization of remote sensing technology to monitor the condition, changes, and vulnerability of mangrove ecosystems shows a clear evolutionary pattern from distribution mapping to more complex, multi-source, and multi-temporal analyzes. Several literatures show that [8] positions remote sensing as an important tool for monitoring the distribution and changes of mangroves globally thru multi-temporal satellite imagery, especially due to its ability to provide extensive area coverage and long-term data continuity. At this phase, remote sensing primarily functions to identify the presence of mangroves, changes in coverage area, and basic spatial dynamics.

The next development is seen in the study by [17], which shows that remote sensing methods do not stop at multispectral images, but rather evolve to the use of radar and LiDAR to read the vertical structure of forests, canopy height, vegetation density, and other biophysical characteristics that are not easily captured by ordinary optical images. The expansion of this type of data indicates that mangrove monitoring methodologies are increasingly moving toward reading the quality and structure of ecosystems, not just their extent. Furthermore, [12] demonstrated methodological advancements in the analytical aspect by utilizing long-term multi-temporal imagery, landscape indices, and clustering methods to interpret spatial change patterns of mangroves over more than four decades. [13] demonstrated that the integration of SPOT-5 and Sentinel-2 images, classification techniques, and vegetation indices enables the monitoring of mangrove cover changes over a decade in a more operational and applicative manner.

The significant meaning of these methodological developments reflects a paradigm shift in mangrove studies. When mangroves are only monitored as land cover objects, the information obtained tends to be limited to how much area is lost or gained. However, when the methodology evolves to be multi-sensor, multi-temporal, and integrated with spatial analysis, mangrove studies can answer much more substantive questions, such as which areas are most vulnerable, what dominant factors are at play, how degradation patterns occur, and what the potential changes in the future might be.

The synthesis results show that the factors most frequently identified in the literature as determinants of the vulnerability or damage levels of mangrove ecosystems can be grouped into three major categories: anthropogenic factors, environmental-physical factors, and biophysical-ecological factors. From the anthropogenic side, [10] demonstrate that the accumulation of marine debris poses a real threat to mangroves. From the environmental-physical side, factors such as sea level rise, hydrological changes, and coastal erosion are significant determinants. Meanwhile, biophysical and socio-ecological factors indicate that the vulnerability of mangroves is the result of the interaction of various interrelated variables. The integration of remote sensing analysis, GIS, and spatial approaches has proven to enhance the effectiveness of monitoring and understanding the dynamics of mangrove ecosystem changes. This integration allows for analyzes that not only detect changes but also explain patterns, causal factors, and future change directions.

IV. CONCLUSION

The use of remote sensing technology in monitoring mangrove ecosystems has evolved into an increasingly important approach in understanding the dynamics of change, vulnerability, and potential damage to coastal ecosystems. Based on the analyzed literature synthesis, the development of remote sensing methodologies shows a shift from simple mangrove distribution mapping approaches to more comprehensive analysis approaches thru the integration of multi-temporal data, various types of remote sensing sensors, and spatial analysis based on geographic information systems. This approach enables the monitoring of mangrove conditions more broadly, systematically, and sustainably over spatial and temporal scales. The study results also show that the vulnerability of mangrove ecosystems is influenced by various interrelated factors, including anthropogenic factors such as pollution and land conversion, environmental factors such as hydrological changes and sea-level rise, as well as biophysical factors related to the structure and condition of mangrove vegetation. The interaction between these factors causes changes in mangrove distribution and increases the potential for coastal ecosystem degradation. Moreover, the integration of remote sensing, GIS, and spatial analysis has proven to enhance the effectiveness of mangrove monitoring by enabling more accurate identification of ecosystem changes and supporting spatial vulnerability analysis. Thus, this research emphasizes that an integrative approach based on geospatial technology plays an important role in understanding the dynamics of mangrove ecosystem changes and provides a strong scientific basis for sustainable coastal management.

The findings of this research make an important contribution to the development of science in the field of coastal ecology and the utilization of geospatial technology in environmental studies. Theoretically, this research reinforces the understanding that the analysis of mangrove ecosystem vulnerability cannot be conducted solely with conventional ecological approaches, but requires the integration of spatial analysis, remote sensing technology, and an understanding of environmental factors as well as human activities that affect coastal ecosystems. The literature synthesis conducted in this study also shows that remote sensing technology not only serves as a tool for mapping mangrove distribution but also as an important instrument in analyzing changes in vegetation structure, ecosystem dynamics, and patterns of coastal vulnerability. In addition, this research provides practical contributions in the form of a framework for understanding the factors that influence mangrove vulnerability, as well as methodological approaches that can be used to monitor ecosystem conditions more effectively. This information can serve as a foundation for policymakers and coastal area managers in designing more targeted mangrove conservation strategies. With the presence of accurate and sustainable spatial data-based monitoring, efforts to protect and rehabilitate mangrove ecosystems can be carried out more systematically. Therefore, this research not only provides academic contributions but also has relevant practical implications in supporting sustainable coastal environmental management.

Nevertheless, this research still has several limitations that need to be considered. This study is based on the synthesis of available literature, so the results obtained are highly dependent on the scope of previously published research. Furthermore, most of the analyzed studies still focus on mapping mangrove distribution and land cover change analysis, while research specifically examining the vulnerability or damage to mangrove ecosystems in an integrated manner remains relatively limited. Therefore, future research is recommended to develop a more comprehensive analytical approach by integrating various sources of remote sensing data, environmental modeling, and socio-ecological analysis related to coastal zone management. Future research also needs to develop mangrove monitoring methods that can identify the vulnerability levels of ecosystems in more detail at both local and regional scales. Additionally, the integration of remote sensing data with field data and socio-economic information from coastal communities can also provide a more comprehensive understanding of the dynamics of mangrove ecosystem vulnerability. Thus, future research is expected to enrich the development of mangrove monitoring methods and support coastal ecosystem conservation efforts more effectively and sustainably.

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