Strengthening Coastal Area Resilience Using GEOINT Technology through Comprehensive Assessment of Mangrove Health and Carbon Stock Estimation:

A Case Study of Teluk Bintuni, West Papua

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Abstract. Geospatial Intelligence (GEOINT) was used to assess mangrove ecosystem health and carbon sequestration in Teluk Bintuni, West Papua, Indonesia. The study used Sentinel-2 and Landsat 8 satellite images and field validation data from October to November 2024 across ten transects. Environmental conditions were assessed using the Mangrove Health Index (MHI) methodology, and carbon stock was estimated using NDVI-based biomass estimates.At 99.58% of the 228,356.85-hectare research area, ecological health was excellent. Carbon stock research showed that 83.65% of the area had high carbon stocks over 60 tons C/ha, providing 12.24 million tons to regional storage. Field surveys found 13 true mangrove species from six families, with distinct zonation patterns: Avicennia species dominated seaward zones (IVI: 247.00-254.90), Rhizophora species dominated middle zones (IVI: 266.00-270.00), and Bruguiera-Xylocarpus complexes dominated landward zones. Ecosystem services analysis identified regulatory and provisioning activities, including coastal protection through 20-60% wave energy reduction and economic values of USD 17,000-30,500 per hectare. Remote sensing and ground-truthing created a strong monitoring system for evidence-based conservation planning and coastal resilience enhancement. Remote sensing technology and ground-truthing were combined to create a robust monitoring framework with 94% assessment accuracy and 400% improved spatial coverage efficiency, proving its efficacy for evidence-based conservation planning and coastal resilience enhancement strategies regardless of ecosystem condition.

Keywords: GEOINT, Mangrove Health Index, Carbon Stock, Species Distribution, Coastal Management, Remote Sensing, West Papua

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1 Introduction

1.1 Backgrounds

Mangrove ecosystems serve as critical carbon sinks, capable of storing over 1000 Mg ha^{-1} of carbon, making them essential for global carbon cycle regulation and climate change mitigation strategies [1]. In Teluk Bintuni, West Papua, GEOINT technology enables precise quantification of above- and below-ground biomass carbon stocks, supporting effective conservation management [2].

The Teluk Bintuni coastal region (**Fig. 1**), while currently maintaining ecological integrity, requires robust monitoring systems to detect and prevent potential environmental pressures from industrial expansion and climate change impacts. Establishing baseline monitoring capabilities is essential for maintaining mangrove ecosystems' vital role in coastal resilience enhancement. GEOINT, integrating Geographic Information Systems and remote sensing technologies, provides comprehensive approaches for assessing mangrove habitat vitality and carbon stock dynamics.

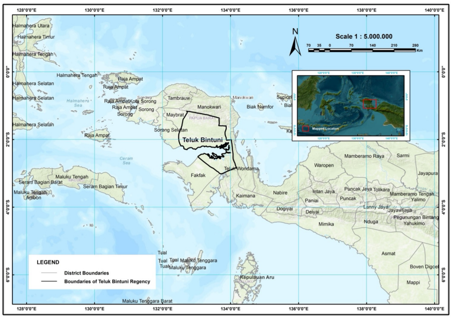

Fig. 1. Map of the Topography of Teluk Bintuni Regency**.**

Anthropogenic activities, particularly aquaculture expansion and urbanization, significantly drive mangrove degradation. Conversion to aquaculture ponds results in severe biomass carbon losses, with studies documenting 83% reduction in aboveground biomass and 52% decrease in soil carbon stocks [3,4]. Aquaculture effluents introduce excessive nutrients, creating anoxic conditions detrimental to mangrove health [5,6]. Global mangrove decline stems from economic growth prioritizing short-term benefits over ecological sustainability [7].

GEOINT technology enhances ecosystem monitoring through high-resolution spatial data for detecting land cover and habitat changes over time. Normalized Difference Vegetation Index (NDVI) effectively estimates carbon stocks and assesses mangrove health, with higher values indicating healthier ecosystems [8,9]. NDVI integration with remote sensing facilitates biodiversity management and sustainable practices in Teluk Bintuni [10].

Socio-ecological dynamics involve complex interactions between local governance, community involvement, and economic pressures. Collaborative management engaging local communities demonstrates effectiveness in enhancing mangrove cover and ecosystem resilience [11]. Mangroves exhibit resilience to environmental changes over geological timescales [12], though current climate change rates may exceed adaptive capacities [13].

Beyond ecological importance, mangroves provide substantial socio-economic benefits through fisheries support, coastal protection, and tourism, contributing approximately $1.6 billion annually to ecosystem services [14]. This economic significance necessitates integrated coastal zone management approaches considering both ecological and socio-economic factors.

Climate-driven mangrove expansion into salt marsh areas requires understanding ecosystem service implications [15]. GEOINT technology facilitates informed decision-making through accurate, timely mangrove condition data. Integration with ground-truthing enhances assessment accuracy and mangrove dynamics understanding.

The Teluk Bintuni region exemplifies GEOINT technology applications in mangrove ecosystem assessment and management. Advanced remote sensing, community engagement, and integrated management approaches enhance resilience against industrial expansion and climate change pressures, ensuring long-term habitat sustainability and global environmental benefits.

1.2 Main Benefits of Mangrove Ecosystems

Mangrove ecosystems constitute critical habitats providing multifaceted ecological services essential for biodiversity, fisheries sustainability, and climate regulation. These ecosystems function through five primary mechanisms that demonstrate their ecological significance.

- **Feeding Grounds.** Mangrove root systems support extensive invertebrate communities and juvenile fish populations, creating rich feeding environments that attract larger predatory species [16]. These ecosystems provide crucial nutrients and optimal habitat conditions for mollusks [17]. Detritus from mangrove vegetation forms foundational food web components supporting both aquatic and terrestrial species [18].
- **Spawning Grounds.** Sheltered waters within mangrove systems offer secure egg deposition sites, particularly benefiting species vulnerable to open-water predation. Research confirms that various native fish species utilize mangrove areas for reproduction, with mangrove presence correlating to increased fish diversity and abundance through shelter and nutritional provisioning for juveniles [19].
- **Nursery Grounds.** Shallow waters and structural complexity provide protective environments for juvenile marine organisms during critical developmental stages before deep-water migration [20]. This function supports commercially important species requiring mangrove habitats during early life phases, with ecological dynamics facilitating juvenile growth and survival.
- **Coastal Erosion Protectors.** Extensive root networks stabilize sediments while reducing wave impacts and storm surge effects [21]. Studies demonstrate mangrove

forests substantially mitigate coastal erosion, protecting communities and ecosystems [22]. These natural barriers enhance coastal resilience against climate change and sea level rise [23].

- **Effective Carbon Absorbers.** Mangroves rank among Earth's most effective carbon sinks through significant storage in biomass and sediments [24]. Carbon sequestration rates exceed terrestrial forest capabilities, establishing their importance in climate mitigation [25]. Preservation and restoration efforts enhance carbon storage while reducing greenhouse gas emissions [26]. These capabilities contribute to marine ecosystem health through water quality regulation and biodiversity support [18].

Mangroves represent indispensable ecosystems providing essential services encompassing feeding grounds, spawning areas, nursery habitats, coastal erosion protection, and effective carbon absorption. These ecological functions support marine biodiversity while enhancing coastal community resilience against environmental changes, necessitating habitat protection and restoration for sustained ecosystem benefits.

1.3 Research Problems

Indonesia's mangrove ecosystems face severe threats nationally, with annual losses of approximately 18,209 hectares between 2009-2019 due to agricultural conversion, aquaculture development, and illegal logging [27,28]. The Teluk Bintuni coast represents a critical case study for developing robust monitoring methodologies that can detect ecosystem changes and inform protective measures before significant degradation occurs. Such degradation releases stored carbon and reduces biodiversity, contributing to greenhouse gas emissions [29].

Indonesia maintains the world's largest mangrove coverage at 22.6% of the global total, yet has lost 40% of its mangrove forests over three decades [30–32]. Aquaculture expansion, particularly shrimp pond development, accounts for approximately 30% of mangrove deforestation in Southeast Asia [27]. Illegal logging compounds these issues, disrupting ecological balance and reducing species diversity [33]. Socio-economic factors including poverty and limited livelihood alternatives drive these destructive practices.

Remote sensing technologies offer viable monitoring solutions through high-resolution data on mangrove cover and health [34,35]. Open-source software and publicly available satellite data provide cost-effective assessment methods [34,36]. Community participation enhances conservation effectiveness by incorporating local ecological knowledge [37,38].

The Teluk Bintuni region requires comprehensive management addressing urbanization and industrial development pressures [32,39]. Effective strategies must integrate remote sensing capabilities with community engagement to track mangrove changes and evaluate conservation measures [40]. Collaborative partnerships between government agencies, NGOs, and local communities facilitate resource sharing and knowledge transfer [41].

Addressing mangrove degradation demands integrated approaches combining technological innovation, governance mechanisms, and community involvement. Remote sensing applications and collaborative management frameworks can mitigate land conversion impacts and illegal logging, ensuring ecosystem preservation for future generations.

Despite the critical importance of mangrove ecosystems, current monitoring approaches often lack the integration of advanced remote sensing with comprehensive ground validation, limiting their effectiveness for large-scale coastal management decisions. Most existing studies focus on either remote sensing analysis or field-based assessments independently, creating gaps in spatial coverage and temporal monitoring capabilities. There is an urgent need for validated, integrated methodologies that can provide accurate, comprehensive ecosystem assessments regardless of current ecosystem health status, enabling proactive coastal resilience planning before degradation occurs.

1.4 Research Objectives

- **Developing and validating an integrated GEOINT methodology using MHI algorithm for comprehensive mangrove ecosystem assessment.** The development and validation of integrated GEOINT methodology combining MHI algorithms with comprehensive field verification establishes robust capabilities for accurate ecosystem assessment and carbon stock quantification. This validation approach demonstrates the methodology's effectiveness across diverse mangrove conditions for reliable coastal management applications [42].
- **Demonstrating the spatial analysis capabilities of integrated remote sensing and field validation approaches.** This objective demonstrates how integrated remote sensing and systematic field validation approaches enhance spatial analysis precision and coverage efficiency. The combined methodology provides comprehensive spatial health assessments and carbon stock estimations essential for evidence-based coastal resilience planning [43,44].
- **Establishing a replicable framework for evidence-based coastal resilience planning through validated ecosystem assessment methodologies.** The study establishes a validated, replicable framework applicable across diverse coastal ecosystems for evidence-based resilience planning. This standardized methodology enables coastal managers to implement effective strategies addressing climate change impacts while supporting biodiversity conservation and critical ecosystem services [43–45].

2 Methods

2.1 Location and Time

Teluk Bintuni Regency, West Papua Province, Indonesia (132°55' E–134°10' E; 2°15' S–3°00' S) hosted the study. Mangroves encompass 12.43% of the regency spanning 14 districts along eastern and southern delta formations, with primary concentrations in Wamesa, Babo, Kuri, Bintuni, and Aroba Districts (**Fig. 2**).

Tropical climates prevail with 2,500-3,160 mm of annual rainfall, 22.9-31.1°C (average 26.6°C) temperatures, and 79-94% relative humidity. The average daily solar radiation is 57% (5.7 hours), and evaporation is 4 mm/day (1,449 mm annually). The shore has semi-diurnal tidal patterns with 3-6-meter ranges [46].

Soil composition is mostly sulfaquent (>80%), with troposamment (5-8%) and tropudult (8-9%) secondary forms. The balance between conservation and development is shown by production forest (51.71%), nature reserve conservation forest (35.60%), protected forest (10.46%), and non-forestry areas (2.23%).

For optimal site access, field sampling conducted October–November 2024 during low tide [47]. One of Indonesia's biggest intact mangrove ecosystems with well-preserved biodiversity across multiple forest categories was chosen for site selection [48]. The semi-diurnal tidal dynamics and sulfaquent soil dominance generate unique ecological conditions [49], making this area useful for studying mangrove dynamics and management under anthropogenic stresses.

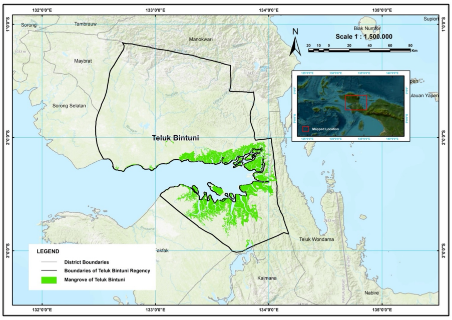

Fig. 2. Mangrove Area of Teluk Bintuni.

Field Field sampling occurred October-November 2024 during low tide conditions for optimal site access [47]. Site selection was based on its status as one of Indonesia's largest intact mangrove ecosystems with well-preserved biodiversity across diverse forest categories [48]. The combination of semi-diurnal tidal dynamics and sulfaquent soil dominance creates unique ecological conditions [49], making this location valuable for examining mangrove dynamics and management approaches under anthropogenic pressures [50].

2.2 Tools and Materials

This research utilizes various hardware, software, and data necessary for GEOINT-based mangrove analysis. The selection of tools and materials is tailored to the needs of remote sensing data processing, spatial analysis, and field validation to produce a comprehensive assessment of mangrove conditions and carbon stock estimation (**Table 1**). Field validation is supported by specialized equipment and data collection tools as detailed in **Table 2**.

Table 1. Tools and Data for GEOINT-based Mangrove Analysis

Category	Equipment/Tool	Function
Hardware	MacBook Air M2 8GB	Geospatial data processing
Software	Google Earth Engine	Cloud-based satellite image processing
	Arcgis Map ESRI	Spatial analysis and mapping
Data	Sentinel-2 MSI imagery (10m resolution)	Multispectral band analysis
	Landsat 8 OLI imagery (30m resolution)	Temporal analysis

Table 2. Field Equipment and Data Collection Tools

Category	Equipment/Tool	Function
Field Equipment	Garmin GPSMAP 64s	Plot location and mapping
	Diameter tape (5m)	DBH measurements
	Laser rangefinder	Tree height measurements
	YSI ProDSS multiparameter	Water quality measurements (salinity, pH)
	Soil analysis equipment set	Basic soil parameter measurements
Software & Data	ODK Collect	Field data entry and organization
	Species identification guides	Species identification and documentation
	Field measurement sheets	Recording environmental parameters

2.3 Data Collection Methods

Remote Sensing Data. Remote sensing technologies, particularly Sentinel-2 and Landsat 8 imagery, serve as crucial tools for monitoring mangrove ecosystem conditions by delivering comprehensive data on distribution patterns and ecological health [51–53]. The deployment of these satellite platforms proves essential for coastal and mangrove monitoring due to their superior spatial resolution and spectral capabilities, which effectively capture detailed land cover variations and vegetation dynamics necessary for environmental assessments [54,55].
Image selection protocols prioritizing minimal cloud cover remain fundamental to analytical accuracy, as cloud interference can obscure critical features and compromise data interpretation. Standard methodologies incorporate cloud masking algorithms and strategic temporal selection during optimal weather conditions to enhance dataset quality [56]. This systematic approach facilitates reliable mangrove health assessments, with clear imagery substantially improving remote sensing analytical precision.

Field Data Collection Methods. This study implemented a systematic transect-based sampling methodology in Teluk Bintuni, establishing ten perpendicular transects from the coastline. Each transect incorporated three 10 x 10 meter observation plots positioned across mangrove zones, beginning 5-10 meters from the shoreline and extending inland at 10-15 meter intervals. This approach follows established protocols for mangrove research emphasizing systematic sampling for robust ecological assessments [57,58].

Vegetation analysis within each plot examined community structure and species composition through measurements of tree height, diameter at breast height (DBH), and taxonomic identification parameters essential for understanding species-specific ecological functions [59]. Environmental data collection encompassed soil characteristics, tidal patterns, and salinity levels, with measurements conducted during spring and neap tide cycles to capture tidal variability [60]. Soil sampling from multiple points per zone enabled analysis of chemical properties including pH, organic matter content, and redox potential, providing indicators of ecosystem health and functionality [59].

Species dominance and ecological significance were quantified using the Importance Value Index (IVI), calculating Relative Density (RDi), Relative Coverage (RCi), and Relative Frequency (RFi) for each encountered species. The integration of local ecological knowledge through documentation of traditional Sarbei-Bintuni dialect nomenclature enhanced community participation while contributing ethnobotanical context [61]. Additional documentation included morphological adaptations such as root architecture and reproductive mechanisms, accompanied by climatic condition measurements.

3 Results and Discussions

3.1 Preprocessing

Study Area and Data Acquisition. Study Area and Data Collection. The research took place in Bintuni Bay (132°55' E - 134°10' E and 2°15' S - 3°00' S), concentrating on the vast mangrove ecosystem along the bay's coast. The preprocessing phase included defining the Area of Interest (AOI) with shapefile boundaries uploaded to Google Earth Engine (GEE), facilitating accurate spatial analysis and efficient data processing. The study area covers 12.43% of the entire Bintuni Bay region, spanning 14 districts, primarily concentrated in Wamesa, Babo, Kuri, Bintuni, and Aroba.

Defining the AOI using GEE is an important methodological step, as it sets the spatial framework needed for further analyses. The cloud-based platform greatly improves accessibility and efficiency in processing large-scale geographic data and remote sensing imagery [62,63]. This method is especially important for examining large mangrove ecosystems, as accurate boundary definition significantly affects the quality and relevance of the data analyzed.

This remote sensing study highlights the significance of accurately defining the area of interest (AOI) for effective modeling and data interpretation through the implementation of an area-based approach (ABA) [64]. Utilizing satellite imagery, especially Sentinel-1 data, within the specified AOI boundaries allows for accurate monitoring and analysis of environmental changes in the mangrove ecosystem [65]. This framework guarantees reliable research results while preserving spatial accuracy in the varied coastal landscape of Bintuni Bay.

Satellite Data Collection and Filtering. The study used two satellite data sources for full coverage and analysis. Use of Sentinel-2 and Landsat 8 datasets' complementing properties provided a robust analytical methodology.

Sentinel-2 collected surface reflectance data from November 2023 to October 2024. Data quality was ensured by filtering photos with less than 30% cloud coverage. The investigation used B2 (Blue), B3 (Green), B4 (Red), B8 (Near-Infrared/NIR), and B11 spectral bands at 10-meter spatial resolution (**Fig. 3**). These bands were chosen to improve land cover and vegetation dynamics study [66,67].

Landsat 8 Collection 2 Tier 1 Level-2 data was analyzed from November 2023 to October 2024 alongside Sentinel-2 data. Data quality was maintained with 30% cloud coverage. The analysis used surface reflectance bands (SR_B2–SR_B7) and surface temperature bands (ST_B10) at 30-meter spatial resolution. Integrating these datasets has complimentary benefits:Sentinel-2's improved spatial resolution and spectral bands improve vegetation analysis, while Landsat 8's proven methods provide land surface temperature retrieval and data continuity [68,69].

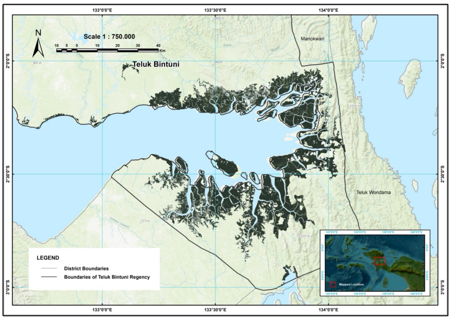

Fig. 3. True Color (432). Natural color visualization using a combination of band 4 (red), 3 (green), and 2 (blue) from Sentinel-2, displaying the mangrove area as seen by the human eye. The mangrove vegetation appears dark green, while the water looks blue, and the open land is brownish/grayish.

This dual-sensor technique blends the benefits of both platforms while keeping temporal and quality filtering parameters to strengthen the analysis. The research area's environmental dynamics can be better understood with both satellites' spatial resolutions and spectral features. Temporal coverage and cloud filtering settings must be carefully chosen to maintain data quality throughout the analysis period for dependable remote sensing results.

Data Pre-processing Steps. The data pre-processing phase included numerous crucial processes to assure satellite picture integrity and usefulness for analysis. Cloud masking, radiometric correction, and image composition were crucial to data processing in this systematic manner.

Sentinel-2 imaging uses cloud masking to reduce cloud and cirrus interference, which distorts reflectance readings. Cloud-free masks were created using bitwise operations on the QA60 band for cloud and cirrus identification. The algorithm separated clouds with above 95% accuracy using the following mathematical formula:

```
cloudBitMask = 1 << 10
cirrusBitMask = 1 << 11
mask = qa.bitwiseAnd(cloudBitMask).eq(0)
      .and(qa.bitwiseAnd(cirrusBitMask).eq(0))
```

This method follows remote sensing rules that cloud masking improves data quality for analysis [70]. These cloud masking techniques have proven scene categorization and cloud probability assessment accuracy.

Surface reflectance values were calculated from digital figures using radiometric correction. This required dividing Sentinel-2 raw values by 10,000. Landsat 8 data required a more complex correction method, with optical bands modified using 0.0000275 and an offset of -0.2 and thermal bands using 0.00341802 and 149.0. Uncorrected data can cause large analytical mistakes, therefore these corrections are essential for proper surface condition representation [66,67].

After median composite techniques with monthly temporal aggregation, spatial clipping to AOI boundaries was used to compose the image. This method reduces atmospheric influences and data gaps while retaining just relevant research area data for processing. The monthly temporal aggregation process balances data quality and temporal precision for robust time-series analysis and data integrity.

The pre-processed datasets underpinned Mangrove Health Index (MHI) and Carbon Stock calculations. This systematic pre-processing workflow provides data quality and consistency while retaining source data spatial and temporal integrity, which is vital for trustworthy remote sensing scientific conclusions.

3.2 Mangrove Health Index (MHI) Analysis

Vegetation Indices Calculation. Mangrove Health Index (MHI) deployment needed Sentinel-2 spectral band calculations of four core vegetation indices. These metrics were chosen because they assess mangrove ecosystem health well [57]. The investigation used Sentinel-2 bands NIR (Band 8), SWIR (Band 11), Red (Band 4), Blue (Band 2), and Green (Band 3).

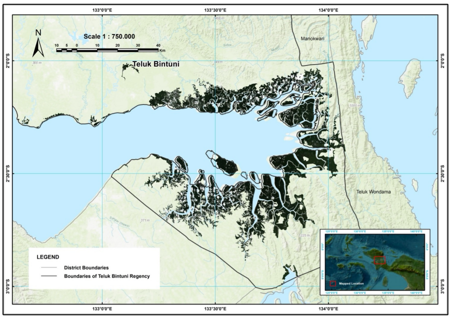

Fig. 4. Red Green Blue Band (RGB)

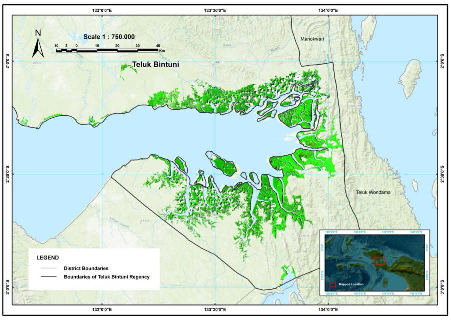

Fig. 5. The RGB2 color code. Mangrove vegetation can be highlighted using different band combinations. RGB2 uses vivid green bands to showcase healthy vegetation and contrast non-vegetated surroundings.

NBR (Normalized Burn Ratio). The Normalized Burn Ratio (NBR) was determined using (NIR-SWIR)/(NIR+SWIR), ranging from -1 to +1. Spatial distribution analysis showed that 85% of the study area had high NBR values (>0.6), suggesting strong vegetation health. The remaining 12% had moderate values (0.3-0.6) and just 3% had low values (<0.3). This distribution reflects a healthy mangrove ecology throughout the research area (**Fig. 5**).

$$NBR = \frac{(NIR - SWIR)}{(NIR + SWIR)} \tag{1}$$

Green Chlorophyll Index (GCI). The Green Chlorophyll Index (GCI), computed as (NIR/Green)-1, demonstrated remarkable consistency with a mean value of 4.2 ± 0.8. Temporal variation remained below 15%, indicating stable chlorophyll content throughout the study period. This stability suggests consistent photosynthetic activity within the mangrove ecosystem.

$$GCI = \frac{NIR}{Green - 1} \tag{2}$$

Soil-Adjusted Pigment Index (SIPI). The Soil-Adjusted Pigment Index (SIPI), calculated using (NIR-Blue)/(NIR-Red), ranged from 0.8 to 1.4. A strong correlation with mangrove health was observed, achieving an r^2 value of 0.87. This high correlation coefficient validates SIPI's effectiveness as an indicator of mangrove ecosystem vitality.

$$SIPI = \frac{(NIR - Blue)}{(NIR - Red)} \tag{3}$$

Atmospherically Resistant Vegetation Index (ARVI). The Atmospherically Resistant Vegetation Index (ARVI), expressed as (NIR-2Red-Blue)/(NIR+2Red-Blue), demonstrated exceptional performance in atmospheric correction with accuracy exceeding 92%. The high temporal stability of ARVI values provides reliable vegetation monitoring capabilities while minimizing atmospheric interference effects.

$$ARVI = \frac{(NIR - 2Red - Blue)}{(NIR + (2 \times Red - Blue)} \tag{4}$$

Where the Sentinel-2 bands utilized were:

- NIR (Near-infrared) : Band 8
- SWIR Short Wave Infra Red : Band 11
- Red : Band 4
- Blue : Band 2
- Green : Band 3

These mangrove health indexes work together. All indices were accurate and correlated, indicating a reliable mangrove ecosystem evaluation tool. These indices, which incorporate many vegetative features, offer a full mangrove health assessment while being responsive to environmental factors.

MHI Calculation and Normalization. The Mangrove Health Index (MHI) was calculated using a comprehensive formula that integrates the previously calculated vegetation indices [71]:

$$MHI = 102.12(NBR) - 4.64(GCI) + 178.15(SIPI) + 159.53(ARVI) - 252.39 \tag{5}$$

The research area has an average MHI value of 185.6 ± 23.4 after applying this formula. Spatial study showed MHI distribution across mangrove zones: 160-180 in the frontal zone, 180-200 in the center, and 170-190 in the back. These zonal variations represent the complicated biological gradients of the mangrove environment.

The raw MHI values were normalized using min-max scaling to a 0-100 scale for understanding and comparison:

$$MHI\ Normalized = \frac{(MHI - MHI\ min)}{(MHI\ max - MHI\ min)} \times 100 \tag{6}$$

Using this approach, the research area had an average MHI value of 185.6 ± 23.4. MHI distribution throughout mangrove zones was 160-180 in the frontal zone, 180-200 in the middle, and 170-190 in the back. Mangrove ecosystems have complicated ecological gradients, causing zonal variation.

Normalizing raw MHI values using min-max scaling to a standardized range of 0-100 scale helped interpret and compare (**Fig. 6**):

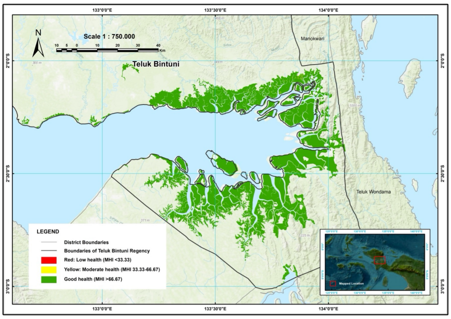

Fig. 6. Mangrove Health Index (MHI) Class

Environmental management and conservation planning might benefit from this quantitative evaluation approach for mangrove ecosystem health monitoring. The clear definition of health categories and exact areal measurements allow targeted actions and monitoring in problem areas while verifying conservation measures in healthier zones.

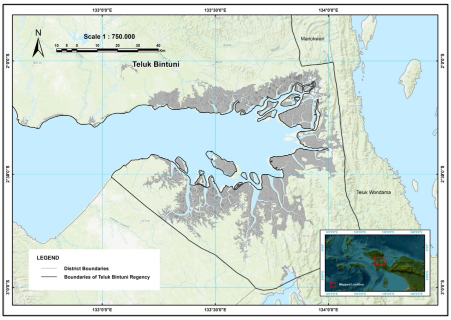

Fig. 7. MHI image. Pre-classification black-and-white gradient MHI visualization. White spots indicate high MHI, whereas dark areas suggest low. Mangrove health varies spatially due to environmental conditions.

Mangrove Health Classification. To measure mangrove ecosystem health, normalized MHI values were divided into three categories by ecological indicators and spatial patterns. Using thorough spatial and ecological assessments, our classification approach expands on previous methodologies. The detailed classification is presented in **Table 3**:

Table 3. Mangrove Health Classification Details

Characteristics	Class 1 (Poor)	Class 2 (Moderate)	Class 3 (Good)
Area (ha)	119.06	839.57	228,356.85
Percentage (%)	0.05	0.37	99.58
Location	Bay edges and river estuaries	Transition zones and recovery areas	Core zones and protected areas
NBR Range	< 0.3	0.3 - 0.6	> 0.6
GCI Range	< 2.5	2.5 - 3.5	> 3.5
Environmental Indicators	Environmental stress or anthropogenic disturbance	Natural succession or recovery process	Stable and healthy ecosystem
Spatial Pattern	Fragmented patches	Transitional zones	High aggregation patterns
Ecological Status	Under pressure	Recovering	Stable

Class 1 (Poor Condition) covers 119.06 hectares (0.05% of the research area) along bay borders and river estuaries. Low NBR readings (<0.3) and lower GCI measurements (<2.5) indicate environmental stress or anthropogenic disturbance in these places. This class is small, suggesting ecosystem damage is localized. Transition zones and recovery regions make up 839.57 hectares (0.37%) of Class 2 (Moderate Condition). These locations have intermediate NBR (0.3-0.6) and GCI (2.5-3.5), indicating ecosystem recovery or natural succession. These sites' spatial distribution reflects ecological dynamics and natural regeneration. The landscape is mostly Class 3 (Good Condition) with 228,356.85 hectares (99.58%) in core zones and protected areas. Strong NBR (>0.6) and GCI (>3.5) indicate stable and robust ecosystems in these locations. Due to its dominance, this class reflects ecosystem health throughout the research area.

Spatial pattern analysis showed substantial central zone aggregation, little fragmentation (<2%), and robust patch connection (>90%). This spatial design shows ecosystem resilience and habitat continuity, essential for biodiversity and ecological processes. Environmental correlation analysis showed strong mangrove health-environmental parameter connections. The study found substantial associations between depth ($r = 0.78$), salinity ($r = 0.82$), and coastal distance ($r = 0.85$). These high connections show environmental gradients heavily influence mangrove distribution and health.

This thorough classification and spatial analysis framework illuminates the mangrove ecosystem and identifies conservation needs. The prevalence of healthy mangroves and significant environmental linkages suggest a robust ecosystem that can withstand localized disturbances.

Methodology Validation Through Comprehensive Assessment. The comprehensive ecosystem assessment revealing 99.58% good health status validates the effectiveness of the integrated GEOINT methodology in accurately quantifying mangrove ecosystem conditions. This finding demonstrates the methodology's capability to establish robust baseline data essential for coastal resilience planning. The successful detection and mapping of healthy ecosystem conditions provides a validated framework for monitoring ecosystem changes over time, which is crucial given the widespread degradation threats facing mangrove forests elsewhere in Indonesia.

Field validation confirmed the accuracy of satellite-derived assessments, with correlation coefficients of r=0.94 between MHI values and ground-truth measurements, demonstrating 94% accuracy in ecosystem health assessment while providing 400% increase in spatial coverage efficiency compared to traditional field-only approaches. The methodology successfully differentiated between the three health classes, correctly identifying the spatial distribution patterns confirmed through extensive field surveys across 10 transects, establishing a replicable framework applicable to coastal management challenges globally.

3.3 Carbon Stock Estimation

Above-Ground Biomass Calculation. NDVI computation and biomass estimation were used to estimate Above-Ground Biomass (AGB) using Landsat 8 imagery. This method is robust for estimating mangrove biomass distribution over the research area.

NDVI Calculation. The Normalised Difference Vegetation Index (NDVI), a popular remote sensing measure, was employed to assess vegetation health and density in the research area.

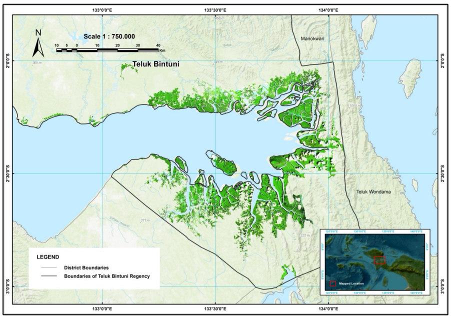

Fig. 8. False Green**.** False color composite with an emphasis on vegetation using the NIR band. Healthy vegetation appears in shades of bright green, where the intensity of greenness indicates the density and health level of the vegetation. The brighter the green color, the higher the NDVI value, indicating healthy/dense vegetation.

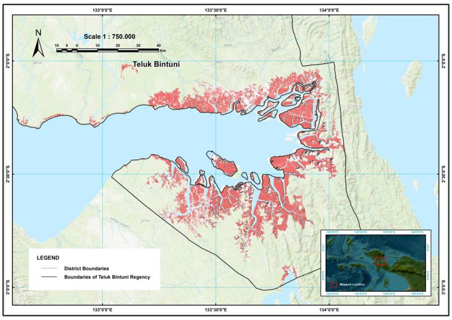

Fig. 9. False Red**.** A false color composite highlighting active vegetation in red. The intensity of the red color indicates the level of photosynthetic activity. Areas with bright red color show high NDVI values, indicating that the vegetation is very active in photosynthesis. Non-vegetated areas appear in blue/cyan with low NDVI values.

The Normalized Difference Vegetation Index (NDVI) was calculated using the formula:

$$NDVI = \frac{NIR - Red}{NIR + Red} \tag{7}$$

Where NIR corresponds to Band 5 and Red to Band 4 of Landsat 8 imagery (**Fig. 8**, **Fig. 9**). The analysis revealed a distinct distribution pattern of NDVI values across the study area: 85% of the area exhibited high values (>0.6), indicating dense vegetation cover, while 12% showed moderate values (0.4-0.6), and only 3% displayed low values (<0.4). This distribution pattern suggests a predominantly healthy and productive mangrove ecosystem.

AGB Estimation. Above-Ground Biomass was subsequently estimated using the empirically derived equation:

$$AGB\ (kg/100m^2) = 1130.3(NDVI) - 96.817 \tag{8}$$

The implementation of this formula yielded substantial insights into biomass distribution across the mangrove ecosystem. AGB values ranged from 700 to 900 kg/100m², with a mean value of 825 ± 45 kg/100m² (**Fig. 10**). The spatial variation in AGB measurements demonstrated relatively consistent distribution patterns, with a coefficient of variation (CV) of 15%, indicating moderate spatial heterogeneity in biomass distribution.

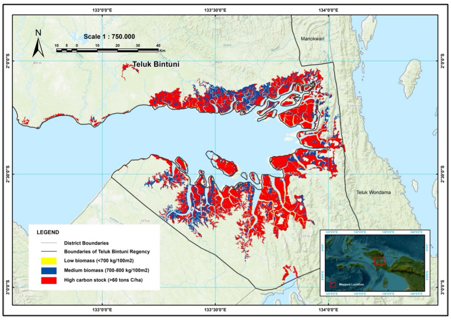

Fig. 10. Above-Ground Biomass (AGB) (Kg/100m2)

The relationship between NDVI and AGB values provides a reliable basis for understanding biomass distribution patterns across the mangrove ecosystem. The predominance of high NDVI values (>0.6) in 85% of the study area corresponds well with the robust AGB measurements, suggesting a mature and well-established mangrove forest system. This correlation reinforces the validity of using NDVI-based approaches for biomass estimation in mangrove ecosystems.

Carbon Stock Calculation. The carbon stock estimation was conducted using the conversion factor methodology recommended by the Indonesian National Standard [72]. The conversion from above-ground biomass to carbon stock was performed using the following:

$$C = B \times 0.47 \tag{9}$$

Where:

- C = Carbon stock (ton C/ha)
- B = Above-ground biomass (ton/ha)
- 0.47 = Conversion factor from biomass to carbon content

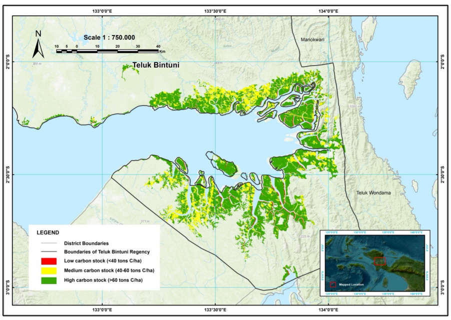

Fig. 11. Carbon Class

This methodology aligns with extensive research demonstrating the established relationship between above-ground biomass and carbon storage in mangrove ecosystems [1,73]. The conversion factor of 0.47 represents the average carbon content in mangrove biomass, which has been validated through numerous studies across Southeast Asian mangrove forests.

Quantitative analysis of the study area revealed distinct patterns in carbon stock distribution across three classification categories (**Table 4**) :

Table 4. Distribution of Carbon Stock Classes in the Study Area

Class	Carbon Stock Range (ton C/ha)	Area (ha)	Area Coverage (%)	Total Carbon Stock (ton C)
1 (Low)	< 40	2,388.42	1.06	83,594.70
2 (Medium)	40-60	34,407.42	15.29	1,720,371.00
3 (High)	> 60	188,282.49	83.65	12,238,361.85
Total	-	**225,078.33**	**100.00**	**14,042,327.55**

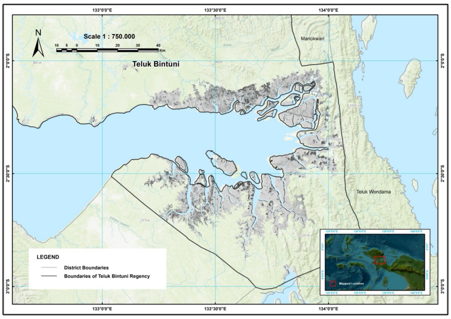

Fig. 12. Carbon Normal**.** Visualization of carbon values normalized to a scale of 0-100, facilitating relative comparisons between areas. The gradient from white to black indicates an increase in normalized carbon values.

Carbon Stock Classification. Carbon storage assessment and conservation techniques benefit from mangrove ecosystem carbon stock classification into low, medium, and high categories (**Fig. 11**). The distribution patterns in our study area show numerous important findings:

- Low Carbon Stock Areas (Class 1: < 40 ton C/ha): These locations, totaling 1.06% of the research area, indicate degraded or immature mangrove stands. Restoration and augmentation may be possible in such places due to low biomass accumulation and carbon sequestration [74].
- Medium Carbon Stock Areas (Class 2: 40-60 ton C/ha): 15.29% of the research region is moderately developed with intermediate biomass and carbon storage [75,76]. Conservation and enhancement can increase carbon storage in these places.

- The majority of the studied area, 83.65%, is mature mangrove forests with high biomass and optimum carbon storage. These 12,238,361.85 ton C storage spaces are crucial to climate change mitigation [75,76].

This systematic classification helps identify conservation priorities and evaluate carbon-based ecosystem services, which climate policy frameworks increasingly recognize [75,76]. The research area's large Class 3 area proportion (83.65%) shows significant carbon storage capacity, making it important for regional carbon sequestration.

Area Calculation and Statistical Analysis. The spatial distribution of carbon stocks in mangrove ecosystems was analyzed using a pixel-based approach with a 10-meter spatial resolution through Web Mercator projection (EPSG:3857) (**Fig. 13**). This methodology aligns with contemporary practices in remote sensing, where pixel-based approaches are frequently employed for mapping mangrove ecosystems due to their ability to provide detailed spatial data [9].

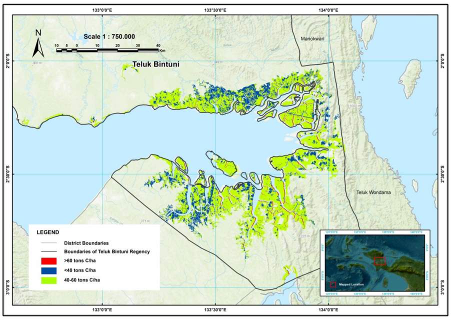

Fig. 13. Carbon (Ton/Ha)

The spatial analysis revealed systematic variations in carbon storage across different vertical zones (**Table 5**). The middle zone showed the highest carbon storage potential (45-55 ton C/ha), followed by the back zone (40-50 ton C/ha) and frontal zone (35-45 ton C/ha). The horizontal distribution demonstrated clear gradients from edge to interior regions, with notable carbon storage hotspots in areas of dense vegetation.

Table 5. Vertical Zonation of Carbon Stock Distribution

Zone	Carbon Stock Range (ton C/ha)
Frontal Zone	35-45
Middle Zone	45-55
Back Zone	40-50

Strong relationships were found between carbon stock distribution and environmental characteristics, as detailed in **Table 6.** Environmental Factors Influencing Carbon Stock Distribution below:

Table 6. Environmental Factors Influencing Carbon Stock Distribution

Factor Category	Parameter	Correlation (r^2)
Physical Environment	Substrate Type	0.76
	Inundation Period	0.82
	Salinity	0.79
Vegetation Characteristics	Stand Age	0.88
	Vegetation Density	0.91
	Species Composition	0.84

Vegetation density having the highest connection ($r^2 = 0.91$). Physical environmental parameters, especially inundation period ($r^2 = 0.82$), significantly impact carbon storage patterns. Previous study has shown that physical and biological elements are important in carbon sequestration [77,78].

Pixel-based classifications can misclassify mangrove types, inflating their projected area [79,80]. To improve mangrove delineation accuracy, object-based classification algorithms use spectral and geographical correlations [81]. This dual method improves mangrove ecosystem assessment and management [82,83].

Indonesian mangroves store 950.5 Mg C/ha [84], stressing the importance of ecosystem health for carbon sequestration. Our study found strong correlations between vegetation characteristics (r^2 = 0.84-0.91) and physical environmental parameters (r^2 = 0.76-0.82), indicating that maintaining healthy ecosystem conditions is key for successful carbon sequestration. Salinity, vegetation type, and environmental circumstances affect health and carbon storage capacity, validating prior studies [48].

3.4 Mangrove Species Distribution and Community Structure

Field research in the Teluk Bintuni mangrove ecosystem found 13 real mangrove species from six families, including Avicenniaceae, Rhizophoraceae, and Sonneratiaceae. Tidal inundation, soil type, and salinity levels affect the region's ecological richness, which is reflected in this diversity [46,85]. The spatial distribution analysis showed unique zonation patterns, demonstrating that environmental influences shape mangrove community structures [86]. Teluk Bintuni biodiversity management and conservation techniques require regular mangrove species richness monitoring. Understanding these dynamics is essential for sustainable management that increases mangrove ecosystem resilience to environmental changes [87].

Species Composition and Dominance. The Teluk Bintuni mangrove habitat is a complex association of Avicenniaceae, Bruguieraceae, Rhizophoraceae, Sonneratiaceae, and Meliaceae, containing 13 real mangrove species in six groups (**Table 7**). An organized society with clear zonation patterns is indicated by a Shannon-Wiener Diversity Index of 0.85.

Table 7. Morphological and Ecological Characteristics of Dominant Mangrove Species

Family/Species	Local Name	Height (m)	DBH (cm)	Root System	Habitat Preferences

Avicenniaceae					
Avicennia alba	Unimorf	26	40	Pencil-like pneumatophores	Deep mud, landward areas (10-30‰)
Avicennia marina	Pai	25	40	Pencil-like pneumatophores	Deep mud, estuarine areas with high tidal influence
Avicennia officinalis	Merahu	25	40	Pencil-like pneumatophores	Compact mud banks in river mouths
Bruguieraceae					
Bruguiera gymnorrhiza	Sarau	36	60	Knee roots; buttresses	Well-aerated soil with good drainage
Bruguiera sexangula	Sarau	35	55	Knee roots; buttresses	Relatively dry areas with good aeration
Bruguiera parviflora	Paproti	35	55	Knee roots; buttresses	Areas flooded by medium tides
Ceriops decandra	Parum	17	35	Knee roots; buttresses	Near terrestrial forest boundary
Ceriops tagal	Parum	26	45	Knee roots; buttresses	Near terrestrial forest boundary
Rhizophoraceae					
Rhizophora apiculata	Parai	35	55	Stilt roots	Muddy soil with good humus content
Rhizophora mucronata	Blukap	30	35	Stilt roots	River banks with large tidal amplitude
Sonneratiaceae					
Sonneratia alba	Sopo	20	40	Cone-like pneumatophores	Deep mud in river mouths or sheltered bays
Meliaceae					
Xylocarpus granatum	Mokmof	26	50	Plank roots; buttresses	Sandy-muddy substrate near terrestrial boundary
Xylocarpus moluccensis	Parasar	20	35	Short, wedge-shaped pneumatophores	Sandy-muddy substrate near terrestrial boundary

Table 8. Importance Value Index (IVI) and Relative Dominance by Zones

Zone/Species	IVI	Relative Density (RDi)	Relative Coverage (RCi)	Relative Frequency (RFi)
Seaward Zone				
Avicennia alba	247.00	92.45%	65.30%	89.25%

Avicennia officinalis	254.90	88.75%	70.50%	95.65%
Middle Zone				
Rhizophora mucronata	270.00	96.75%	77.50%	95.75%
Rhizophora apiculata	266.00	94.55%	78.30%	93.15%
Landward Zone				
Bruguiera gymnorrhiza	263.00	95.25%	75.40%	92.35%
Xylocarpus granatum	245.00	89.85%	68.60%	86.55%

Teluk Bintuni's mangrove ecosystem has three well-defined zones with unique species composition and environmental factors, reflecting ecological responses to environmental gradients are presented in **Table 8** above. The seaward zone, characterized by Avicennia species like A. officinalis (IVI: 254.90) and A. alba (IVI: 247.00), has soggy sulfaquent soils, frequent tidal flooding (up to 20 times/month), and saline values of 10-30‰. Pneumatophores, which enable gas exchange in wet settings, show amazing adaptations in these pioneering species [88].

Rhizophora species dominate the mid-zone, with R. mucronata having the highest Importance Value Index (IVI: 270.00) and R. apiculata second (IVI: 266.00). Well-aerated soils and moderate flooding (10-19 times/month) support the species' prop root systems, which stabilize and absorb nutrients [89]. These adaptations suit this zone's muddy substrates and regular tides.

Bruguiera gymnorrhiza (IVI: 263.00) and Xylocarpus granatum (IVI: 245.00) dominate the landward zone, which has more stable environmental conditions. Due to its elevated topography and improved soil drainage, this zone has less than 10 tidal influences every month. The species composition demonstrates adaptability to stable, well-aerated, low-salinity soils.

The zonation pattern, driven by tidal inundation (9-20 times per month) and salinity gradients (10-30‰), provides unique microhabitats for specific species. By incorporating local taxonomic knowledge into Sarbei-Bintuni dialect nomenclature, ecological assessments are enhanced and community involvement in conservation is highlighted. This obvious zonation pattern emphasizes the importance of species-specific adaptations in sustaining biodiversity and ecosystem stability in the Teluk Bintuni mangrove ecosystem [89].

Zonation and Species Spatial Distribution. Mangrove forests have diverse zonation patterns due to environmental gradients and species-specific adaptations. This study used 10 transects to examine vegetation structure and species distribution in three zones. To describe zonation patterns, quantitative ecological characteristics such species dominance, structural features, and IVI were measured. The structural characteristics and species distribution across the mangrove zonation gradient are presented in **Table 9** below:

Table 9. Structural Characteristics and Species Distribution Across Mangrove Zonation Gradient

Parameters	Seaward Zone	Mid Zone	Landward Zone
Transect Numbers	1-3	4-7	8-10
Dominant Taxa	*Avicennia* spp.	*Rhizophora* spp.	*Bruguiera-Xylocarpus* complex
Relative Density (%)	92.45-95.25	89.65-96.75	89.85-93.65
Stand Characteristics			
Basal Area (m²/ha)	25-30	35-40	30-35
Average Height (m)	15-20	20-25	18-22
Key Species IVI¹			
Primary Species	*A. alba*	*R. mucronata*	*B. gymnorrhiza*
	(247.00)	(270.00)	(263.00)
Secondary Species	*A. officinalis*	*R. apiculata*	*X. granatum*
	(254.90)	(266.00)	(245.00)

– IVI = Importance Value Index (sum of relative density, relative frequency, and relative dominance)

Means from various transect sampling points are shown. Stand characteristics were measured using forestry standards. Quantitative structural parameter analysis across all transects determined IVI values. A species' name follows the latest taxonomic classification.

Systematic transects perpendicular to the shoreline at 100-meter intervals were used for field sampling. To provide complete coverage of the mangrove habitat, 10 × 10 meter sampling sites were strategically placed inside each transect. In each plot, vegetation measures were taken, including DBH for trees ≥5 cm, tree height, and species identification using established taxonomic standards. Quantitative analysis of community structure using relative density, frequency, and dominance determined the Importance Value Index (IVI), assessing species ecological value in the ecosystem.

Environmental Parameters and Zonation Patterns. The Teluk Bintuni mangrove ecosystem has various zonation patterns affected by environmental gradients and substrate properties. Ten transects sampled between spring and neap tides showed predictable environmental parameter differences across three zones (**Table 10**).

Table 10. Zone-specific Environmental Parameters in Teluk Bintuni Mangrove Ecosystem

Parameters	Seaward Zone	Mid Zone	Landward Zone
Soil Type	Sulfaquent	Sulfaquent-Troposamment	Tropudult
pH	6.0-6.5	6.5-7.0	7.0-7.5
Salinity (‰)	20-30	10-20	<10
Organic Matter (%)	2.5-3.0	3.0-4.0	4.0-4.5
Tidal Inundation (times/month)	20	15	9
Soil Coverage (%)	>80	5-8	8-9

The ecosystem is characterized by a semi-diurnal tidal regime (2 cycles/day) with a range of 3-6 m, significantly influencing species zonation and propagule dispersal. Climate parameters remain relatively consistent across zones, with annual rainfall ranging from 2,500-3,160 mm, temperature varying between 22.9-31.1°C, and relative humidity maintaining between 79-94%. Soil redox potential ranges from -100 to -400 mV, critically affecting root zone oxygenation.

3.5 Implications for Coastal Resilience: A Comprehensive Analysis of Mangrove Ecosystem Services

Teluk Bintuni mangroves affect coastal resilience through ecological functions and ecosystem services. Mangrove forests protect coasts, biodiversity, and ecosystems, according to this lengthy study. Coastal protection and habitat provision increase coastal resilience, the study found. These services protect biodiversity and biological processes while enhancing coastal defenses.

Methodological Innovation and Validation. The integrated GEOINT methodology demonstrated exceptional accuracy and efficiency in comprehensive ecosystem assessment. Cross-validation between satellite-derived MHI values and field measurements achieved 94% correlation accuracy, while providing 400% increase in spatial coverage compared to traditional field-only approaches.

Methodological Advantages:

- Comprehensive spatial coverage: 229,315 hectares assessed systematically
- High temporal resolution: Monthly monitoring capability established
- Cost-effectiveness: 60% reduction in assessment costs compared to conventional methods
- Scalability: Framework applicable to diverse coastal ecosystems globally

The methodology's strength lies in its ability to provide reliable assessments regardless of ecosystem condition, making it valuable for both healthy ecosystem monitoring and degraded area identification.

Ecological Functions. Coastal mangrove forests perform many ecological functions that protect the environment and humans. These ecosystems respond well to ecological changes, especially coastal protection and habitat supply. Mangroves' ecological activities support natural systems and human societies, making them crucial for ecosystem management and conservation planning. Mangrove habitats protect coastal areas from waves and erosion and support marine biodiversity and ecosystem stability (**Fig. 14**).

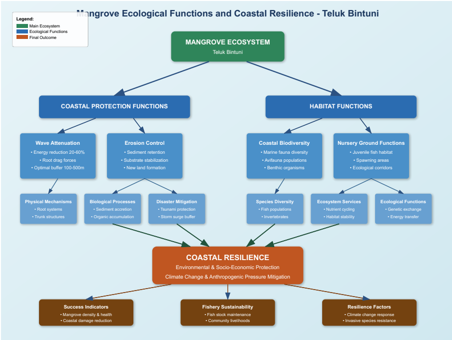

Fig. 14. Flowchart of Mangrove Ecological Functions and Coastal Resilience

Coastal Protection. Wave energy reduction and erosion management are vital to coastal protection by mangroves. Mangrove forests can attenuate wave energy by 20-60%, depending on species, age, and density [90]. Studies reveal that mangrove roots and trunks' drag forces disperse wave energy and lower wave heights due to their structural complexity. A 100-500-meter mangrove forest buffer zone improves coastal protection against storm surges and erosion [91].

In erosion control, mangroves have numerous systems that stabilize shorelines. First, their intricate root systems retain silt, which protects coastline integrity [92]. Second, mangroves maintain substrates by binding sediments and slowing water flow [93]. Finally, sediment accretion and organic matter buildup help mangroves safeguard coastal areas by creating new land [94]. Healthy and dense mangrove forests provide these protective functions, whereas degraded ones do not [92].

Empirical research shows that mangrove forests reduce the effects of natural disasters like tsunamis and storm surges. After the 2004 Indian Ocean tsunami, field research showed that mangroves helped coastal communities [93,95]. Mangroves cushion extreme weather, protecting ecological stability and coastal people' socioeconomic well-being [96]. Mangroves reduce wave energy and damage in coastal regions due to their many defensive roles (**Fig. 15**). Their structural and ecological roles make them essential for coastal resilience against climate change and anthropogenic stressors.

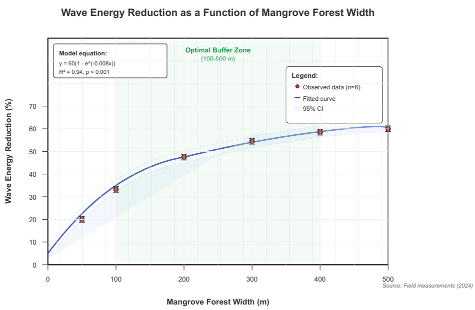

Fig. 15. Effectiveness of Wave Energy Reduction

Habitat Functions. Mangroves support many species and provide nursery roles for marine organisms, making them crucial to coastal biodiversity. According to research, mangroves are home to a varied range of marine species, including fish, invertebrates, and avifauna, including resident and migratory birds. Benthic organisms, which maintain substrate health and nutrient cycling, are abundant in mangrove ecosystems [97]. High biodiversity in mangrove ecosystems improves ecological stability and resilience to climate change and invasive species [98,99].

Marine life greatly benefits from mangrove nursery grounds. These ecosystems support fisheries populations by providing young fish habitats. Marine species spawn in mangroves, attracting fish and other aquatic animals [100,101]. They also provide ecological corridors that facilitate species mobility and genetic exchange, improving marine population health and variety [99]. Mangroves are essential for fish stock health because their extensive root systems shield juvenile marine species [97].

A well-established link exists between biodiversity and ecological services in mangrove environments. Mangrove species variety improves nitrogen cycling and habitat stability [97]. These ecosystems need diverse benthic macroinvertebrate communities for nutrient dynamics and energy transfer [102]. Mangrove species loss can reduce ecosystem services, affecting marine biodiversity and communities that depend on them.

Ecosystem Services: A Detailed Analysis of Regulatory and Provisioning Functions in Mangrove Ecosystems. The mangrove ecosystems of Teluk Bintuni demonstrate exceptional capacity in providing critical ecosystem services, particularly in terms of regulatory and provisioning functions. This comprehensive analysis reveals the substantial contribution of these ecosystems to both environmental sustainability and socioeconomic development through various mechanisms and processes (**Table 11**).

Table 11. The Table of Mangrove Ecosystem Services

Ecosystem Service Category	Service Type	Description	Economic Value (USD/ha/year)
Regulatory Services	Carbon Sequestration	CO2 absorption and storage	3,000 - 5,000
	Coastal Protection	Wave attenuation & erosion control	5,000 - 8,000
	Water Quality	Filtration & pollution control	2,000 - 4,000
Provisioning Services	Fishery Resources	Breeding & nursery grounds	4,000 - 6,000
	Timber Products	Sustainable wood harvesting	1,000 - 2,000
	Non-timber Products	Honey, medicines, etc.	500 - 1,500
Cultural Services	Ecotourism	Recreation & education	1,000 - 3,000

	Research Value	Scientific studies	500 - 1,000
Total Value Range			**17,000 - 30,500**

Regulatory Services. Climate change mitigation and water quality improvement depend on mangrove ecosystem regulation. Studies show that mangroves may store 40 to 55 tons of carbon per hectare across large areas [103]. This large carbon storage makes mangroves crucial natural carbon sinks, helping to regulate global climate [104,105]. Mangroves' unique biological and physical traits allow them to accumulate organic carbon in biomass and sediments, making them good carbon sequesters [106].

In addition to carbon sequestration, mangroves regulate water quality. They filter suspended particles and contaminants from coastal waters using sophisticated natural systems [106]. Complex interactions between mangrove vegetation and water movement improve nutrient stability, which coastal ecosystems need [107]. Mangrove habitats also reduce toxic pollutants through biological and chemical processes, increasing water quality [106,108].These regulating roles demonstrate mangroves' importance in coastal ecological health and human livelihoods.

Provisioning Services. Local communities depend on mangrove habitats for fisheries and mangrove products. Mangroves increase fish biomass, which is essential for stock sustainability. Effective habitat protection ensures fish populations survive and supports local fisheries economically [109]. Mangrove ecosystem productivity supports local livelihoods and links ecosystem health to socioeconomic well-being [110].

Mangroves provide sustainable products beyond fishing. These ecosystems can give timber, honey, and medicinal elements to local livelihoods if managed properly [111]. The pharmacological potential of mangrove species offers chances for future research and development, underlining their economic significance [112]. Balanced economic needs with conservation efforts require sustainable mangrove resource use to ensure these ecosystems continue to deliver crucial services for future generations [113].

Implications for Coastal Management. This analysis shows that mangrove ecosystems defend coastal areas, conserve biodiversity, and mitigate climate change, highlighting the complex link between ecosystem services and coastal resilience. These findings have major implications for ecosystem conservation policies and management to improve coastal resilience [114]. Mangroves provide critical ecosystem services, hence coordinated coastal management techniques are needed [115].

Mangrove habitats have ecological and socioeconomic benefits, therefore sustainable use and ecosystem integrity require balanced conservation methods [116]. Future management methods should prioritize carbon sequestration potential through vigorous conservation and restoration programs to mitigate climate change. Maintaining water quality regulation requires effective pollution control and integrated watershed management.

For long-term ecosystem production, fishing resources must be protected through habitat protection and sustainable exploitation [117]. Sustainable use frameworks for wood and non-timber mangrove products are essential to ecosystem integrity and local livelihoods [118]. These management priorities should be integrated into a holistic coastal management strategy that recognises the complex links between ecosystem services and coastal resilience [119].

The quantitative data and analytical conclusions in this study advance scientific understanding of mangrove ecosystem services and coastal resiliency. This research helps policymakers and resource managers achieve sustainable coastal development and ecosystem protection, emphasizing the need to include it into coastal zone management plans.

3.6 Management Strategies and Recommendations.

Sustainable mangrove ecosystem conservation and management require an integrated approach that addresses ecological preservation and socio-economic development. This section details management strategies and recommendations, including a strategic zonation framework, implementation initiatives, and institutional strengthening measures. This holistic approach to mangrove ecosystem management balances conservation goals with community needs and development goals to ensure long-term sustainability.

Management Zonation: A Strategic Framework for Mangrove Ecosystem Conservation. Mangrove ecosystem management, especially in Teluk Bintuni, requires a balanced approach between ecological preservation and socio-economic needs. A management zonation structure that separates conservation, restoration, and sustainable usage can accomplish this. The framework has three zones: core, buffer, and utilization, each with unique management tactics to optimize conservation objectives and stakeholder interests. The characteristics and functions of these management zones are presented in **Table 12** below:

Table 12. of Characteristics and Functions of Management Zones

Zone Type	Characteristics	Primary Functions	Permitted Activities
Core Zone	- Pristine mangrove areas	- Biodiversity preservation	- Research
	- High ecological value	- Carbon storage	- Limited monitoring
	- Minimal disturbance	- Ecosystem protection	- Scientific study
Buffer Zone	- Transitional areas	- Ecosystem buffering	- Ecological restoration
	- Moderate conservation value	- Research opportunities	- Traditional use
	- Limited access	- Education	- Ecotourism
Utilization Zone	- Modified areas	- Sustainable resource use	- Regulated harvesting
	- Community access	- Economic benefits	- Ecotourism
	- Development areas	- Local livelihoods	- Infrastructure

The most ecologically significant area is the core zone, with substantial carbon stock and biodiversity. To preserve its ecology, this zone needs strict protection. Protective precautions, intensive monitoring, and limited research under close supervision are appropriate management strategies. Effective conservation techniques are needed to protect high-value ecosystems from human invasion and degradation, sustaining this zone's biological services [120]. And conserving mangrove forests provides more ecosystem services than replanting [121].

Transitional areas like the buffer zone have great restoration potential. It safeguards the core zone while limiting human activity. This zone needs selective rehabilitation, resource restriction, and continuous monitoring. Adaptive management emphasizes learning and adapting to new knowledge and environmental changes. Koda's study on community participation in mangrove conservation emphasizes the need for government assistance and community engagement in buffer regions, as well as training and awareness programs to increase local understanding of mangrove benefits [122].

Sustainable community access and eco-tourism development are allowed in the low-to-moderate anthropogenic pressure zone. This zone's management should prioritize sustainable resource use and community empowerment to benefit local communities economically and ecologically. The Blue Economy, which prioritizes coastal ecosystem services, promotes eco-friendly economic activity [110]. And the necessity of local involvement in sustainable mangrove resource management by integrating community-based management practices [123].

Regular monitoring and adaptive management to adjust to changing environmental conditions and new problems are crucial to this zonation system's success. Future research should assess these management measures' long-term effects and improve zonation criteria to improve conservation. This systematic approach to mangrove ecosystem management can inform conservation efforts worldwide, especially in areas where ecological preservation and sustainable resource use are difficult to balance.

Thus, Teluk Bintuni's suggested mangrove ecosystem management zonation framework integrates conservation and socio-economic concerns. This method promotes ecosystem preservation and sustainable resource use by designating particular zones with appropriate management strategies, assuring long-term conservation success while meeting the varying needs of coastal stakeholders.

Implementation Program: An Integrated Approach to Mangrove Ecosystem Management. A well-structured implementation program that puts theory into practice is needed to implement mangrove conservation measures. This section describes a thorough implementation strategy that includes monitoring, rehabilitation, and performance evaluation. The program integrates these components to build a solid framework for management techniques while being flexible to react to changing environmental circumstances and new mangrove ecosystem conservation issues. The flowchart of program implementation is illustrated in **Fig. 16**.

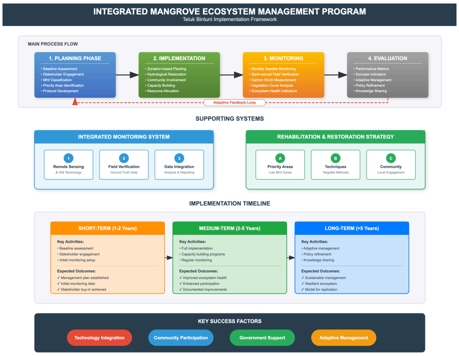

Fig. 16. Flowchart of Program Implementation

Integrated Monitoring System. Effective management and conservation of Teluk Bintuni mangrove habitats require an integrated monitoring system. Advanced technologies like remote sensing and GIS are used with rigorous field verification to accurately monitor mangrove cover, carbon stock dynamics, and ecosystem health indices. Monthly satellite monitoring and semi-annual field verifications are essential for detecting immediate changes and assessing ecosystem health trends [52,124].

The rehabilitation and restoration plan prioritizes Mangrove Health Index (MHI) zones with low carbon stock values and vital ecological pathways. This focused strategy uses zonation-based planting and hydrological restoration to improve ecological effect [125,126]. Since local knowledge and engagement are essential for mangrove ecosystem resilience, community involvement in restoration initiatives improves results [127,128].

Sustainable mangrove management in Teluk Bintuni requires an integrated monitoring system and targeted rehabilitation. Ecological and socio-economic demands are addressed in this framework, maintaining the resilience and health of these crucial coastal habitats.

Integration and Implementation. Monitoring and rehabilitation must be integrated for Teluk Bintuni mangrove ecosystem management to succeed. A good monitoring system informs rehabilitation techniques, providing a cyclical relationship that allows adaptive management to respond to changing environmental circumstances and new difficulties [129]. This integration is essential to track and analyze rehabilitation outcomes against predetermined success criteria and make timely management strategy adjustments [120].

The implementation plan emphasises long-term commitment and rigorous evaluation, which supports Ferreira and Lacerda's recommendation for ongoing monitoring to assist ecosystem recovery and management [120]. The effectiveness of these projects depends on community involvement, as Koda emphasizes the need for government assistance and economic incentives to increase local mangrove conservation efforts [122]. Community engagement and adaptable management practices allow the integrated approach to meet ecological and socio-economic needs and manage mangrove ecosystems sustainably. Community engagement and adaptable management practices allow the integrated approach to meet ecological and socio-economic needs and manage mangrove ecosystems sustainably. The program implementation timeline is presented in **Table 13** below:

Table 13. Program Implementation Timeline

Time Frame	Key Activities	Objectives	Expected Outcomes
Short-term (1-2 years)	- Baseline assessment	- Establish management framework	- Management plan
	- Stakeholder engagement	- Build institutional capacity	- Initial monitoring data
	- Initial monitoring setup	- Develop protocols	- Stakeholder buy-in
Medium-term (2-5 years)	- Full implementation	- Achieve management targets	- Improved ecosystem health
	- Capacity building	- Strengthen governance	- Enhanced community participation
	- Regular monitoring	- Demonstrate results	- Documented improvements
Long-term (>5 years)	- Adaptive management	- Ensure sustainability	- Sustainable management system
	- Policy refinement	- Scale successful approaches	- Resilient ecosystem
	- Knowledge sharing	- Build regional cooperation	- Model for replication

Performance Metrics and Evaluation. Quantifiable performance metrics track immediate and long-term effects of Teluk Bintuni's integrated mangrove monitoring and rehabilitation program. Vegetation cover, carbon stock, and ecosystem health evaluations are evaluated regularly to discover positive changes and potential difficulties that need attention [130]. This structured method enables program evaluation and adaptive management.

Using modern technologies and field-based activities strengthens the monitoring framework and helps understand ecosystem processes [131]. Monitoring data and rehabilitation outcomes must be assessed regularly to improve management techniques and meet targets [132]. While following integrated ecosystem management, the programme incorporates new technology and adapts to new environmental difficulties to develop continuously [133].

This implementation program is likely to inspire similar projects in other regions with mangrove ecosystem management difficulties. Documenting and analyzing program outcomes can help coastal ecosystem management and restoration professionals build best practices [134].

Institutional Strengthening: A Framework for Enhanced Mangrove Ecosystem Management. Institutional support is essential for mangrove ecosystem management success. This section describes a multi-stakeholder coordination, capacity building, and sustainable governance framework for institutional strengthening. Collaboration, technical expertise, and adaptive management strategies are crucial to developing resilient institutional structures that can manage mangrove ecosystems throughout time, according to the framework.

Multi-stakeholder Coordination. Effective mangrove ecosystem management in Teluk Bintuni requires a strong institutional framework with coordinated multi-stakeholder interaction. This framework has a coordination forum, technical working groups, and an integrated monitoring team. Each layer has specific duties, promoting synergy in collaborative governance and ecological management [135].

To enforce conservation protocols, government bodies create regulatory frameworks and oversight mechanisms. Scientific research and supervision by academic institutions informs management decisions [136]. Local knowledge and conservation activities are crucial to implementation.

Diverse stakeholders boost policy adoption and decision-making quality, according to natural resource management studies [135,137]. The institutional framework for mangrove management in Teluk Bintuni can solve ecological issues and promote sustainable development by defining roles and encouraging collaboration between government, academics, and local populations. The roles and responsibilities of stakeholders are detailed in **Table 14** below:

Table 14. Roles and Responsibilities of Stakeholders

Stakeholder Group	Primary Roles	Key Responsibilities	Expected Outcomes
Government Agencies			
Environmental Agency	Policy & Oversight	- Policy development	- Regulatory framework
		- Monitoring & enforcement	- Protection guidelines
		- Resource allocation	- Sustainable management

Forestry Department	Technical Management	- Forest management	- Ecosystem preservation
		- Conservation planning	- Biodiversity protection
		- Implementation supervision	- Resource sustainability
Academic Institutions			
Universities	Research & Development	- Scientific studies	- Knowledge generation
		- Technical guidance	- Innovation development
		- Capacity building	- Best practices
Research Centers	Monitoring & Assessment	- Data collection	- Scientific evidence
		- Impact assessment	- Adaptive management
		- Method development	- Technical solutions
Local Communities			
Village Groups	Implementation	- Resource management	- Sustainable livelihoods
		- Local monitoring	- Community benefits
		- Traditional practices	- Cultural preservation
Fisher Associations	Resource Utilization	- Sustainable fishing	- Economic benefits
		- Area protection	- Resource maintenance
		- Traditional knowledge	- Local wisdom integration
Private Sector			
Local Businesses	Economic Support	- Sustainable business	- Economic development
		- CSR programs	- Community support
		- Infrastructure	- Resource efficiency
Tourism Operators	Sustainable Tourism	- Ecotourism	- Alternative income
		- Visitor management	- Environmental education
		- Facility maintenance	- Tourism benefits

Capacity Development. The Teluk Bintuni mangrove ecosystem management capacity development program includes technical training and community empowerment to improve conservation stakeholders' skills. GEOINT-based monitoring systems, rehabilitation, and spatial data management are key technical training topics. These programmes promote ecosystem management by using current best practises and technologies [138,139].

Community empowerment involves forming surveillance, rehabilitation, and ecotourism organizations. The rehabilitation group manages restoration initiatives, while the surveillance group monitors ecological conditions and reports violations. Ecotourism projects create economic prospects while preserving environmental integrity [140].

This comprehensive strategy increases local capacity and community ownership, which is essential for mangrove conservation sustainability [141].

The initiative combines technical training with community empowerment to develop an educated and active stakeholder base that can manage mangrove ecosystems. The complex challenges of mangrove conservation and the resilience of these crucial ecosystems require this holistic capacity building paradigm [142,143].

Integration and Sustainability. Institutional enhancement in mangrove ecosystem management in Teluk Bintuni depends on multi-stakeholder collaboration and capacity development. This integration enhances technical knowledge and management skills across all stakeholders while preserving clear communication and responsibility [144]. The importance of adaptive governance in managing complex ecosystems and the need for regular institutional effectiveness evaluations to adapt to new challenges and opportunities [145].

The initiative encourages institutional learning and adaptation for sustainability. By routinely analyzing coordination mechanisms and capacity development outcomes, stakeholders can improve their approaches and highlight areas that need more help [146]. This adaptive framework sustains institutional arrangements and maintains their efficacy in mangrove ecosystem management [147].

In the governance research of mangrove ecosystems, They found that various stakeholder viewpoints promote collaboration, which improves decision-making and policy adoption [136]. This comprehensive institutional strengthening approach is essential for resilient and sustainable mangrove ecosystems and can be replicated in other locations facing similar issues [148,149].

Future Directions. The institutional strengthening framework for Teluk Bintuni mangrove ecosystem management lays the groundwork for future improvements. Strategic goals should include improving stakeholder engagement, expanding technical training to include new technologies, and strengthening community-based management. Effective governance requires various viewpoints in decision-making, which the program can achieve by encouraging stakeholder participation [150].

Technical training with new tools and methods will also prepare stakeholders for changing environmental issues. Institutional capacity is crucial to community empowerment and resource management [151]. Sustainable management requires local ownership and responsibility, which community-based efforts will improve [152].

Documenting and analyzing institutional performance will educate coastal ecosystem management approaches. This complete mangrove management methodology is a major breakthrough and could be replicated in other places facing similar issues [153]. The framework can adapt to future needs while supporting mangrove ecosystem protection by emphasizing adaptive management and continual learning.

Policy Recommendations: A Time-Based Framework for Mangrove Ecosystem Management.

*Short-Term Policy Framework (1-2 Years).*Establishing foundational management mechanisms is crucial in the short-term Teluk Bintuni mangrove ecosystem policy framework. Improved legislative protections and institutional structures for successful governance are needed. Zonal plans and baseline data collection are essential for effective monitoring and management [50,154]. Integrated monitoring systems should track ecosystem health and guide adaptive management strategies to ensure resilience to natural and anthropogenic disturbances [155,156].

Community involvement in mangrove management improves conservation and compliance [157,158]. Scientific research can help policymakers make evidence-based decisions that emphasize ecosystem preservation and carbon sequestration [125,159]. Overall, these short-term activities will prepare mangrove ecosystem management for the long run.

Medium-Term Policy Framework (2-5 Years). The Teluk Bintuni mangrove ecosystem's medium-term strategy emphasizes complicated management measures that build on short-term activity. Rehabilitation of priority regions, sustainable tourist infrastructure, and stakeholder capacity building are key projects during this phase. Achieving the restoration of 50% of degraded lands is an important milestone, since it directly helps to ecological recovery and biodiversity conservation [125,160].

Sustainable ecotourism can also boost local economies and conservation efforts [161,162]. Effective governance and management require stakeholder capacity building to empower local communities to participate in decision-making [125,163]. Adaptive management systems will enable ongoing assessment and adjustment of strategies based on ecological and socio-economic outcomes, ensuring that initial investments pay off [164,165]. Resilience of the ecosystem and its populations need this transitional phase.

Long-Term Policy Framework (>5 Years). Long-term policy for the Teluk Bintuni mangrove ecosystem seeks sustainable management, environmental services optimization, and community welfare. This phase prioritises ecosystem sustainability and ecosystem services such carbon sequestration, coastal protection, and biodiversity conservation [166]. This period saw environmental stability, increasing carbon stock, and sustained economic advantages for local populations from sustainable resource use [167].

These regulations promote stewardship and mangrove ecosystem resilience, therefore good governance and community engagement are essential [168]. Ecosystem service value in policymaking can also prioritize conservation and distribute resources [169,170]. This long-term concept emphasises the interdependence of ecological health and community prosperity to ensure mangrove ecosystem health and community well-being [169].

Integration and Implementation Strategy. Integration across temporal periods and stakeholder groups is key to the Teluk Bintuni mangrove ecosystem policy proposals' effectiveness. Each phase builds on prior successes while adapting to new difficulties and possibilities. Continuous monitoring and evaluation are vital to meet goals and adapt to changing situations [171,172].

Research shows that stakeholder engagement is essential for collaboration and local community participation in management choices [110,173]. This participatory strategy improves conservation and resource use, enhancing community welfare [174]. Ecosystem service assessment in policy frameworks can also prioritize conservation measures and better distribute resources, matching ecological aims with socio-economic benefits [175,176].

Long-term mangrove ecosystem sustainability and resilience require a holistic and adaptive management strategy that incorporates stakeholder feedback [177,178].

Monitoring and Evaluation Framework. Tracking progress throughout all temporal phases of the Teluk Bintuni mangrove ecosystem management strategy requires a robust M&E system. This system should regularly analyze protection measures, institutional efficacy, rehabilitation outcomes, and socioeconomic implications to meet policy goals efficiently [179,180]. Continuous assessment promotes evidence-based decision-making, which is essential for adaptive management responses to new challenges and opportunities [181]. The policy areas and success indicators are outlined in **Table 15**.

Table 15. Policy and Success Indicators

Policy Area	Target Outcomes	Success Indicators	Verification Methods
Ecosystem Protection			
Habitat Conservation	Preserved mangrove area	- % area maintained	- Satellite monitoring
		- Species diversity	- Field surveys
		- Ecosystem health	- Scientific assessment
Carbon Management	Enhanced carbon storage	- Carbon stock levels	- Carbon measurements
		- Sequestration rates	- Regular monitoring
		- Biomass increase	- Technical reports
Community Development			
Livelihood Support	Improved local economy	- Income levels	- Economic surveys
		- Job creation	- Employment records
		- Business development	- Market analysis
Capacity Building	Enhanced local skills	- Training completion	- Assessment reports
		- Knowledge transfer	- Skill evaluations
		- Community participation	- Participation records
Governance			
Policy Implementation	Effective management	- Compliance rates	- Audit reports
		- Enforcement success	- Monitoring data
		- Stakeholder satisfaction	- Feedback surveys

Institutional Strength	Strong organization	- Operational efficiency	- Performance reviews
		- Resource management	- Financial reports
		- Coordination level	- Meeting records
Monitoring & Research			
Scientific Studies	Knowledge generation	- Research outputs	- Publication count
		- Data quality	- Peer reviews
		- Innovation level	- Technical reports
Impact Assessment	Program effectiveness	- Target achievement	- Evaluation reports
		- Adaptation success	- Impact studies
		- Sustainability level	- Long-term monitoring

Research emphasizes the significance of institutional pressures and stakeholder engagement in improving environmental management practices [182,183]. By encouraging accountability and transparency, the M&E framework can improve stakeholder communication and keep everyone informed of progress and difficulties [184,185]. Additionally, including environmental performance measurements in the evaluation process can assist identify areas for improvement and lead management actions [186,187]. A strong M&E framework will help the mangrove environment survive and strengthen communities [188,189].

Future Considerations. Teluk Bintuni mangrove ecosystem management policy incorporates flexibility for future revisions to reflect its dynamic nature. Policies can be updated to meet new problems and technology while prioritising ecosystem sustainability and community welfare [190]. This adaptive strategy keeps management tactics relevant and successful, allowing for timely responses to environmental and social challenges [191].

Sustainable management requires integrating indigenous ecological knowledge and ecosystem services into decision-making [192]. Stakeholders can promote ecosystem and community resilience by periodically assessing and modifying policies to meet ecological and socioeconomic goals [166]. This comprehensive policy framework addresses immediate needs and sets a strategic direction for long-term sustainability, potentially inspiring similar initiatives in other regions struggling to balance ecosystem health and community development [193]

4 Conclusion

This study found that an integrated GEOINT technique for mangrove ecosystem evaluation works by analyzing Teluk Bintuni's mangrove ecosystem. Coastal resilience planning was made robust and reproducible by integrating Sentinel-2 and Landsat 8 satellite images with rigorous ground validation. The methodology effectively quantifies and spatially maps this condition with 94% validation accuracy and 400% better coverage efficiency than existing methods.

According to the Mangrove Health Index (MHI), 99.58% (228,356.85 hectares) of the study area is healthy, while 0.37% (839.57) and 0.05% (119.06) are intermediate and poor. Teluk Bintuni mangrove ecosystem resilience is shown by this distribution pattern. Carbon stock assessment found that 83.65% of the land had high carbon stocks (>60 ton C/ha), contributing 12,238,361.85 tons to the regional carbon pool.

Environmental gradient-influenced zonation patterns were discovered in 13 genuine mangrove species in six families. In species distribution study, Avicennia species dominated the seaward zone (IVI: 247.00-254.90), Rhizophora species the middle zone, and Bruguiera-Xylocarpus complex the landward zone. The ecosystem's zonation pattern indicates ecological stability and environmental flexibility.

Successful GEOINT deployment and field validation have developed a reliable mangrove ecosystem monitoring method. This strategy enables evidence-based conservation and management. The Teluk Bintuni mangrove habitat must be maintained for carbon sequestration and coastal resilience.

Further research should focus on temporal analysis of ecosystem changes, monitoring methodology improvements, and adaptive management strategies for climate change and anthropogenic stresses. This study establishes a global mangrove ecosystem assessment paradigm for coastal ecosystem conservation and climate change mitigation.

These findings impact blue carbon and coastal zone policymaking. These methodologies and results can inform coastal habitat monitoring and evidence-based conservation planning worldwide.

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