Biosaintifika 17 (1) (2025): 128-142 p-ISSN 2085-191X | e-ISSN 2338-7610
Journal of Biology & Biology Education https://journal.unnes.ac.id/nju/index.php/biosaintifika

Coastal Erosion Reduces Resilience and Disrupts Compositional Dynamics of The Mangrove Ecosystem

Andin Irsadi[1*], Abdul Jabbar[2], Nur Kusuma Dewi[1], Dadang Somantri[3], Amar Sharaf Eldin Khair[4], Wahid Akhsin Budi Nur Sidiq[5], Dhita Pracisca Mutiatari[6], Nana Kariada Tri Martuti[1]

[1]Department of Biology, Faculty of Mathematics and Natural Science, Universitas Negeri Semarang. Jalan Raya Sekaran Gunungpati, Semarang City, 50229, Indonesia
[2]Department of Integrated Science, Faculty of Mathematics and Natural Science, Universitas Negeri Semarang, Jalan Raya Sekaran Gunungpati, Semarang City, 50229, Indonesia
[3]Bureau of Infrastructure and Natural Resources, Central Java Regional Secretariat, Jalan Pahlawan No. 9, Semarang City, 50249, Indonesia
[4]Department of Geography, Omdurman Islamic University, Omdurman City, Sudan
[5]Department of Geography, Faculty of Mathematics and Natural Science, Universitas Negeri Semarang. Jalan Raya Sekaran Gunungpati, Semarang City, 50229, Indonesia
[6]Department of Community Empowermen, Yayasan Akar Banir Indonesia, Perumahan Green Village, Ngijo, Gunungpati, Semarang City, Central Java, Indonesia. 50228.

*Corresponding Author: andin.sha@mail.unnes.ac.id

Submitted: 2024-12-11. Revised: 2025-02-15. Accepted: 2025-04-14.

Abstract. Indonesia's coastline, particularly Kendal Regency in Central Java, faces critical mangrove degradation due to land-use changes and rising sea levels. This study aims to asses the condition and erosion impacting Kendal's mangrove ecosystems to inform future conservation strategies. Using remote sensing technology, multi-spatial and multi-temporal imagery from 2005–2023 was analyzed and validated with field observations to evaluate mangrove species composition, structure, and land changes. The mangrove area increased by 52% in three locations, with the Bodri River delta (Pidodo Kulon and Pidodo Wetan villages) showing the most significant growth at 76.69 hectares. Ngebum Beach (Mororejo) had the largest proportional increase, reaching 185%. The ecosystems are moderately diverse, containing at least 11 mangrove species, though Rhizophora dominates due to extensive planting efforts. Despite stable conditions, these ecosystems face threats from deforestation for aquaculture, the primary driver of land erosion, compounded by rising sea levels. Although mangrove areas have expanded significantly, ongoing challenges include erosion, anthropogenic pressures, and limited species diversity. Future strategies must involve multi-stakeholder collaboration to implement sustainable practices, promote species diversity, develop erosion mitigation models, and conduct awareness campaigns to ensure the resilience of Kendal's mangrove ecosystems.

Keywords: Coastal erosion; Mangrove Ecosystem; multitemporal; Compositional Dynamics

How to Cite: Irsadi, A., Jabbar, A., Dewi, N. K., Somantri, D., Khair, A. S. E., Sidiq, W. A. B. N., Mutiatari, D. P., & Martuti, N. K. T. (2025). Coastal Erosion Reduces Resilience and Disrupts Compositional Dynamics of The Mangrove Ecosystem. *Biosaintifika: Journal of Biology & Biology Education, 17(1)*, 128-142.

DOI: http://dx.doi.org/10.15294/biosaintifika.v17i1.17292

INTRODUCTION

Indonesia's coastline spans 95,181 km and hosts an estimated 3.5 million ha of mangrove forests, representing 23% of the global mangrove expanse. This diverse ecosystem encompasses approximately 40 of the 50 true mangrove species found worldwide (World Bank, 2021). Mangroves play a vital role in sustaining coastal environments, providing habitats for various fish, shrimp, and bird species by serving as foraging, spawning, and shelter grounds (Akram et al., 2023). Additionally, mangroves act as carbon sinks (Hashim & Suratman, 2021) and heavy metal pollution absorbers (Sundaramanickam et al., 2021), functioning as instruments for climate change mitigation (Kumari & Rathore, 2021), protecting coastlines from erosion (Irsadi et al., 2022), preventing saltwater intrusion (Hilmi et al., 2017), serving as educational and recreational resources (Afifah et al., 2023; Kamaruddin et al., 2023), and providing alternative livelihood opportunities (Fikri et al., 2022; Mitra, 2020).

Despite their significance, Indonesia's

mangrove ecosystems face severe threats from land-use conversion for aquaculture, industrial zones, and urban settlements, leading to forest fragmentation (Cahyaningsih et al., 2022; Rudianto et al., 2020). In Central Java’s Kendal Regency, rapid development, including the Kendal Industrial Estate (KIE), tiger shrimp farming, and tourism expansion, has accelerated mangrove loss. By 2031, KIE alone is projected to convert 1,593.5 ha of mangroves and ponds into industrial areas (Damastuti et al., 2022). In recent years, the coastal area of Kendal Regency has experienced rapid land-use conversion due to development activities, including establishing the Kendal Industrial Estate (KIE), cultivating tiger shrimp and milkfish ponds, and developing tourism and industries. The development of the KIK poses a significant threat to the preservation of mangrove areas as it is projected to convert approximately 1,593.5 ha of ponds and mangroves into industrial and commercial areas by 2031 (Sadewo & Buchori, 2018). Erosion has already claimed up to 792 m of shoreline in the region (Kurniawan & Marfai, 2020).

Given the current challenges, comprehensive mapping of coastal areas and a detailed inventory of mangroves are vital to assess the extent of degradation and evaluate the environmental carrying capacity of the coastal zone as a foundation for effective rehabilitation. This requires tracking the development and status of mangroves over time, including their spatial distribution, area, density, and species composition. This study aims to asses the condition and erosion impacting Kendal's mangrove ecosystems to inform future conservation strategies. This research enhances the understanding of mangrove resilience, biodiversity, and climate change mitigation while also informing coastal zoning regulations and policy recommendations. Furthermore, it helps stakeholders and local communities promote disaster risk reduction, and economic development aligns with environmental sustainability.

METHODS

This study was conducted in the coastal region of Kendal Regency, focusing on villages with extensive mangrove ecosystems and significant exposure to erosion and accretion, including Mororejo (MR), Kartikajaya (KJ), Pidodo Wetan (PW), and Pidodo Kulon (PK). Remote sensing technology was utilized to produce multi-spatial and multitemporal imagery data of coastal land-use changes, which were subsequently validated through field observations and direct measurements (Muxiye & Yonezawa, 2023; Niculescu et al., 2018)

Mangrove Ecosystem Structure Analysis

Field observations were conducted to assess the species composition, abundance, distribution, and coverage of mangroves at each sample site. A standardized classification system was employed to categorize mangrove stands based on their size and type. Mature mangrove trees, representing the well-established woody canopy layer, were identified as individuals potentially reaching heights of up to 25 m with a diameter at breast height (DBH) ranging from 10 to 50 cm, depending on the species. Saplings, locally referred to as "stang," were defined as having diameters between 2 and 5 cm and heights from approximately 1 to 5 m. Seedlings were distinguished by diameters of less than 2 cm and heights below 75 cm. Species identification was conducted using online databases, notably the Wetlands Indonesia platform (https://www.wetlands.or.id/mangrove/mangrove_species.php?id=11). The structural characteristics of the mangrove ecosystem were analyzed using ecological metrics to evaluate the ecosystem's health and functional quality, as detailed in Table 1.

The Shannon's diversity index (H') and Simpson's dominance index (D) were subsequently interpreted based on the category values detailed in Table 2.

Table 1. The formula for calculating ecological metrics index and parameters of mangrove ecosystem structure in Kendal Regency.

Parameters/ Index	Formula	
Number of individuals (N)	The Number of individual species in a quadrant area of observation.	
Species dominance (ha)	Total Basal Area (BA) of a species expressed in the area (ha)	
Relative dominance (%/ Ha)	$= \frac{\text{Species dominance (ha)}}{\text{Total dominance (ha)}} \times 100$	(1)
Species Density (Ind/ ha)	$= \frac{\text{Individuals number of a species in the sample area (Ind)}}{\text{Area of the sample plot (ha)}} \times 100$	(2)
Relative Density (%/ ha)	$= \frac{\text{Species density}}{\text{Total density of all species}} \text{ x } 100$	(3)
Species Frequency (%)	$= \frac{\text{Number of quadrats where a species is present}}{\text{Total Number of quadrats}} \times 100$	(4)
Relative Frequency (%)	$= \frac{\text{Species frequency}}{\text{Total frequency of all species}} \times 100$	(5)
Important value index (IVI)	$= \text{Relative Dominance (\%)} + \text{Relative Frequency (\%)} + \text{Relative Density (\%)}$	(6)
Diversity Index/ Shannon Diversity Index (H')	$= -\sum_{i=1}^{S} (p_i \times \ln(p_i))$	(7)
Evenness Index (E)	$= \frac{H'}{H_{max}}$ Where Hmax = ln(S), S = number of species found	(8)
Dominance Index/ Simpson's Dominance Index (C)	$= 1 \sum_{i=1}^{S} (p_i^2)$	(9)

Note: pi = proportion of individuals belonging to species *i* in the total sample. Developed based on ecological methodology following (Krebs, 1989; Odum, 1971; Ulfah et al., 2019)

Table 2. The diversity and dominance indices criteria and interpretation.

Index	Score	Criteria	Interpretation
Shannon Diversity Index (H')	> 3.00	High diversity	Higher values indicate greater diversity.
	1.00 – 3.00	Moderate diversity	Lower values indicate lower diversity.
	< 1.00	Low diversity	Values close to 0 suggest extreme dominance by a single species.
Evenness Index (E)	> 0.75	Stable community	Species are distributed relatively equall in abundance. This score suggests a stable and mature community with minimal dominance by a single species.
	0.50 – 0.75	Unstable community	A mix of dominant and less common species exists. This score could indicate a community in transition or one with moderate environmental pressures.
	< 0.50	Depressed community	One or a few species are highly dominant, with others being scarce. This score may suggest a stressed or unstable community, potentially impacted by disturbances or competition.
Simpson's Dominance Index (C)	> 0.75	High dominance	Measures dominance of the most abundant species. Higher values indicate high dominance (more even distribution).
	0.50 – 0.75	Moderate dominance	Lower values indicate higher dominance by a single or few species.
	< 0.50	Low dominance	Values close to 0 suggest near-complete dominance by a single species.

Note: Developed based on the ecological methodology following Krebs (1989); Odum (1971); Ulfah et al. (2019).

Mangrove Mapping and Spatial Analysis

High-resolution satellite imagery from 2005 to 2023 was used to assess mangrove ecosystem development in Kendal Regency. Geometric corrections were applied using the image-to-map method, aligned with Indonesia's National Map for spatial accuracy. Imagery was cropped to coastal sub-district boundaries, focusing on mangrove habitats to streamline data storage and analysis.

Table 3. Mangrove condition and quality categories based on canopy density and cover

Category	Density (Ind/Ha)	Canopy Cover (%)
Good/Healthy	> 1500	> 75
Medium	1000 – 1500	50 – 75
Bad/Damaged	< 1000	< 50

Note: The standard refers to the Decree of the Ministry of Environment of the Republic of Indonesia No. 201 of 2004

Mangrove delineation and digitization techniques were employed for spatial distribution mapping, with density classified using a 5x5 mm pixel size. ArcGIS 10.8 was used for overlay analysis and tracking land cover changes. Imagery from Maxar Technologies underwent geometric correction for precise coordinate assignment. Field surveys validated mangrove distribution and density, confirming species composition and enabling species-specific mapping. Mangrove cover was categorized based on density and canopy cover, following Indonesian Ministry of Environment Decree No. 201/2004, ensuring robust spatial and temporal analyses for sustainable mangrove management.

Data analysis techniques

Findings on threats, challenges, and mangrove ecosystem management efforts were validated using spatial maps, including mangrove distribution for 2005 and 2023, mangrove cover changes from 2005 to 2023, density maps, and species distribution maps in Kendal Regency's coastal areas. This data was analyzed descriptively to produce a comprehensive narrative detailing potential threats and conservation strategies for mangrove ecosystems.

RESULTS AND DISCUSSION

Changes in the Growth of the Mangrove Ecosystem

Visual analysis of mapped areas in 2010, 2011, 2015, and 2023 highlights a significant expansion of mangrove coverage in four sampling villages. Growth was concentrated in three primary regions: the Bodri River delta (Pidodo Wetan and Pidodo Kulon villages), the Kartikajaya village coastline, and Ngebum Beach in Wonorejo village (Figure 2).

Figure 2. An overview of satellite images at the research location based on the results of calculating changes in mangrove areas.

Table 4. The area of mangrove ecosystems at the research site in 2023

Research Site	Administrative Region	Mangrove Forest Area (Ha)				Change* (%)
		2000	2011	2015	2023	
Bodri river delta	Pidodo Kulon Pidodo Wetan	48.68	68.10	70.98	76.69	57.54
			+19.42	+2.88	+5.71	
Kartikajaya coastline	Kartikajaya	27.01	23.45	34.30	31.86	17.96
			-3.56	+10.85	-2.44	
Ngebum Beach	Mororejo	4.99	7.42	12.73	14.25	185.57
			-3.56	+10.85	+1.52	
Total ecosystem		80.68	98.97	118.01	122.80	52.21
			+18.29	+19.04	+4.79	

Note: *) total change in mangrove area from 2000-2023 through visual interpretation of images. The -/+ sign on the cell's row indicates the shift in mangrove area during the observation period, where the tanga minus (-) refers to the decrease in the area of mangrove area in Ha, while the (+) sign refers to the increase in the area of mangrove area.

The mapping analysis indicates a significant increase in mangrove coverage of over 52.21% across the three study areas from 2000 to 2023 (Table 4). The findings reveal distinct patterns of mangrove growth and decline. The Bodri River delta showed the most substantial mangrove expansion, followed by a period of decline and subsequent recovery. In contrast, the Kartikajaya coastline exhibited a more complex trajectory, characterized by an initial loss of mangrove area, followed by growth and then decline. Ngebum Beach displayed a relatively steady pattern of mangrove expansion, although at a slower rate compared to the Bodri River delta. These varying trends suggest that multiple factors are influencing mangrove dynamics in the region. The Bodri River delta appears to benefit from a more stable sediment supply and reduced wave energy, while the Kartikajaya coastline may be more vulnerable to human-induced disturbances, including land-use changes and pollution.

The mangrove conditions at the research sites exhibited annual variations, documented through time-series mapping of mangrove ecosystem development using high-resolution satellite imagery and visual interpretation. Further analysis of the satellite imagery revealed distinct spatial distribution patterns of mangroves at each research location. In the Bodri River delta, the mangrove community displayed an aggregated distribution along the coastline, characterized by high canopy density. This clustered spatial distribution was also observed at the centers and edges of large fishponds (> 400 m²) but not along the embankments of the ponds (Figure 3). Mangrove ecosystems are inherently dynamic, with their area subject to expansion or reduction due to various factors such as land-use change, erosion, mangrove rehabilitation efforts, and other environmental influences (Bhagarathi & DaSilva, 2024; Cahyaningsih et al., 2022).

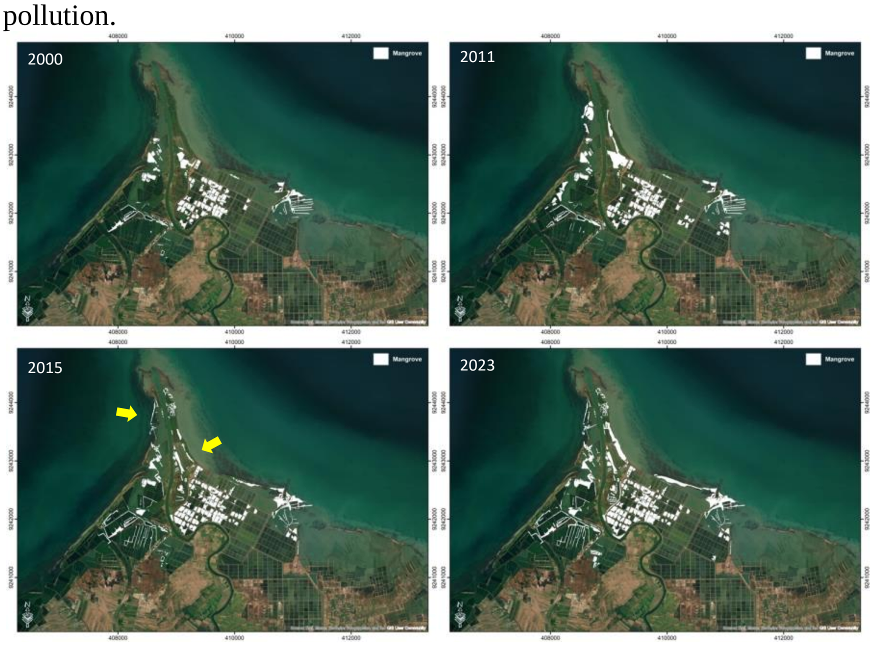

Figure 3. Spatial distribution of mangroves in the Bodri River delta 2000. 2011. 2015 and 2023. The highlighted area in white shows the mangrove area.

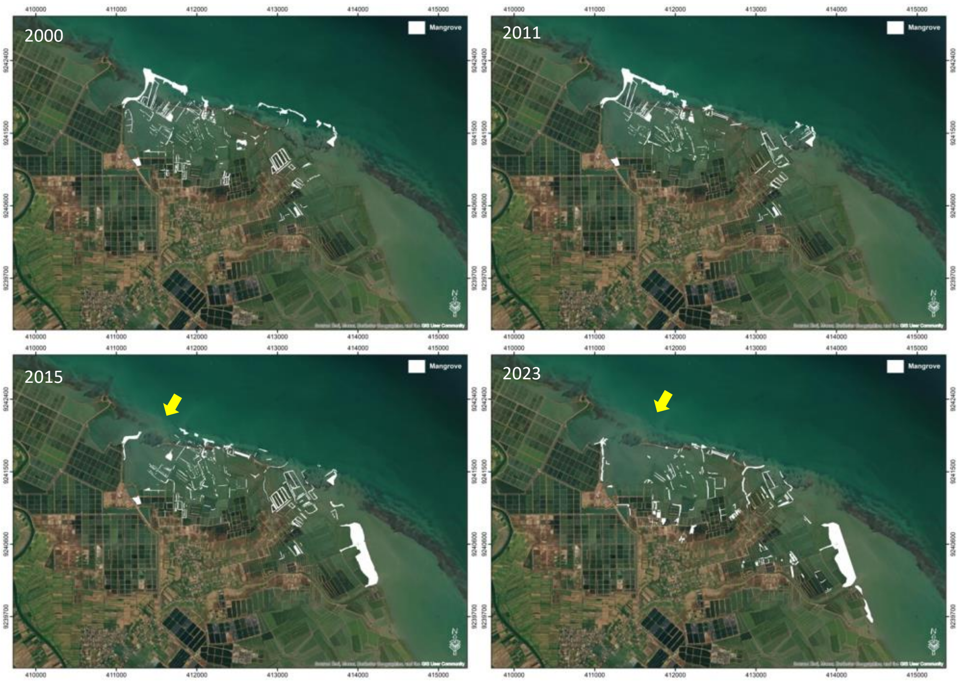

Figure 4. Spatial distribution of mangroves on the coast of Kartikajaya village in 2000. 2011. 2015 and 2023. The highlighted area in white shows the mangrove area.

The mangroves in the Bodri River delta exhibited a consistent trend of area expansion over the years. Between 2000 and 2011, the mangrove area increased by 19.42 ha, primarily along the eastern and western regions of the Bodri River mouth, following an elongated pattern along the river and coastline (Figure 3). This expansion was largely attributed to planting efforts by the local government and communities in prior years. A further increase in mangrove area was observed from 2011 to 2015, albeit on a smaller scale of approximately 2.88 ha. This growth was concentrated in the southern region, mainly along fishpond embankments, where local fish farmers had initiated a planting program to protect their ponds from erosion. However, during this period, a decline in mangrove area was also noted due to erosion damaging the roots of mangrove seedlings and saplings. From 2015 to 2023, the Bodri River delta saw another expansion of 5.71 ha, with growth along the coastline and the river mouth characterized by a continuous increase in canopy density.

In Kartikajaya Village, the spatial distribution of mangroves predominantly follows an elongated, aggregated pattern along fishpond embankments, with relatively low canopy density. A decline in the mangrove area was observed along the northern coastline, likely due to erosion. In contrast, the eastern region, which directly faces the sea, saw increased mangrove cover, distributed in a regular, elongated, and clumped pattern, with higher canopy density. This expansion effectively mitigated erosion caused by waves (Figure 4).

The mangrove ecosystem along the Kartikajaya village coastline displayed a dynamic and fluctuating trajectory. Between 2000 and 2011, the northeast coastline of Kartikajaya experienced a mangrove loss of approximately 3.56 Ha due to wave erosion. This erosion removed sediments and growth substrates, rendering the environment unsuitable for mangrove seedlings. However, between 2011 and 2015, a significant expansion of mangrove area occurred, increasing by 10.85 Ha, primarily in the eastern region adjacent to the coastline and partially along fishpond embankments (Figure 4). During the subsequent period from 2015 to 2023, mangrove coverage declined by approximately 2.44 Ha. This reduction may be attributed to increased anthropogenic activities, particularly the expansion of fishponds by local communities, which likely impacted the stability of the mangrove ecosystem.

In contrast, a substantial increase in mangrove area was observed at Ngebum Beach in Mororejo Village. Ngebum Beach, initially exhibiting the smallest mangrove cover among the three study sites, showed notable growth. A spatial analysis of mangrove distribution at Ngebum Beach reveals that most mangroves are distributed in an elongated pattern along fishponds, characterized by low canopy density (Figure 5).

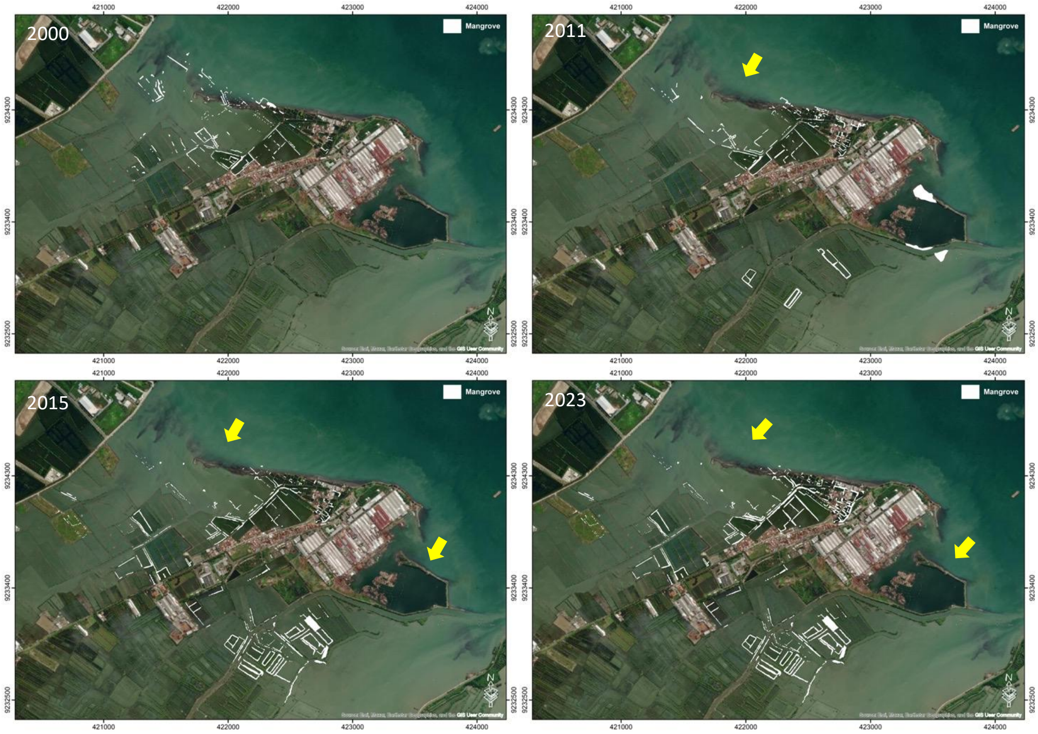

Figure 5. Spatial distribution of mangroves in Ngebum Beach in 2000. 2011. 2015 and 2023. white highlights represent mangrove areas

Mangrove growth around Ngebum Beach experienced a significant annual increase, with the mangrove area expanding by 2.43 Ha between 2000 and 2011. This expansion continued from 2011 to 2015, with an additional 5.31 Ha of mangrove cover, and further increased by 1.52 Ha between 2015 and 2023. The mangroves around Ngebum Beach are primarily distributed in an elongated pattern along fishpond embankments, characterized by low canopy density. Field observations indicated that the decline in mangrove areas across all study sites was mainly due to land-use conversion for productive fishery and shrimp farming activities. In contrast, the expansion of mangrove areas was largely driven by seedling planting efforts aimed at protecting community fishponds. These initiatives were supported by government-led coastal rehabilitation programs and growing awareness among coastal communities in North Java about the importance of environmental conservation. Furthermore, the scale of mangrove planting is expected to increase further due to the heightened recognition of the detrimental effects of sea-level rise and erosion on community fishponds (Maulidah et al., 2023).

Distribution Zone and Composition of Mangroves

Field observations revealed distinct mangrove zonation patterns across the four study sites, each characterized by specific species and varying levels of diversity (Table 6). However, mangrove growth at some sites showed inter-zonal species mixing and irregular patterns. This phenomenon is likely the result of planting activities carried out by communities, the government, or private entities for rehabilitation purposes.

Field observations identified at least 11 species, comprising nine true mangrove species and two mangrove associates (Table 6). In Mororejo Village, seven species were recorded: Avicennia marina, *A. officinalis*, *Leucaena leucocephala*, Rhizophora apiculata R *mucronata* R *stylosa*, and *Talipariti tiliaceum*. In Kartikajaya Village, six species were identified: *A. marina*, *A. officinalis*, *Bruguiera gymnorrhiza* R *apiculata* R *mucronata*, and *R. stylosa*. Pidodo Wetan harbored five mangrove species: *A. marina*, *A. officinalis* R *mucronata* R *stylosa*, and *Xylocarpus moluccensis*. Pidodo Kulon also exhibited five mangrove species: *A. alba*, *A. marina*, *Excoecaria agallocha* R *mucronata*, and *R. stylosa*. Mangrove community data was further categorized into three growth stages: tree sampling, sapling sampling, and mangrove seedling sampling.

Table 6. Types of mangroves obtained on the Kendal Coast

Species	Vern Name	MR	KJ	PW	PK	Type
Avicennia alba	Api-api hitam				√	True-Mangrove
A. marina	Api-api putih	√	√	√	√	True-Mangrove
A. officinalis	Api-api ludat	√	√	√		True-Mangrove
Bruguiera gymnorrhiza	Tancang		√			True-Mangrove
B. agallocha	Buta-buta				√	True-Mangrove
Excoecaria agallocha L.	Buta-buta				√	True-Mangrove
Leucaena leucocephala	Mlanding	√				Associated-mangrove
Rhizopora apiculata	Bakau minyak	√	√			True-Mangrove
R. mucronata	Bakau hitam	√	√	√	√	True-Mangrove
R. stylosa	Bakau kurap	√	√	√	√	True-Mangrove
Talipariti tiliaceum	Waru	√				Associated-mangrove
Xylocarpus moluccensis	Nyiri batu			√		True-Mangrove
Total species		7	6	5	5	

Note: MR = Desa Mororejo, KJ = Kartikajaya, KJ = Pidodo Wetan, dan PK = Pidodo Kulon.

Mangrove Community Structure

Analysis of the seven identified species revealed diverse mangrove community structures across the observation sites (Table 7). The Mororejo Village ecosystem is composed of six tree stand species, along with the presence of the sapling-stage species *L. leucocephala*. This ecosystem exhibits good stability, characterized by moderate to low dominance and moderate diversity. These conditions indicate that the Mororejo Village ecosystem's species are evenly distributed, with no single dominant species. This condition can have a significant ecological function, as balanced ecosystems are often more resilient to environmental changes and disturbances while maintaining ecosystem functions and services more effectively (Canty et al., 2022; Rahman et al., 2024). This evenness in species distribution can enhance the ecosystem's ability to provide critical services such as carbon sequestration, coastal protection, and habitat provision for diverse fauna. At the tree level, *A. marina* holds the highest importance value, while *R. mucronata* exhibits the highest importance values for saplings and seedlings. These findings suggest that *A. marina* and *R. mucronata* may play pivotal roles in shaping the mangrove ecosystem in Mororejo Village. Both species exhibit adaptations to environmental stressors such as salinity and siltation, with *A. marina* showing specific anatomical adaptations like increased stomatal density to maintain hydraulic conductivity under siltation stress (De Deurwaerder et al., 2016). Furthermore, *R. mucronata*'s ability to thrive in mixed populations with *A. marina* enhances the overall carbon sequestration and ecological resilience of mangrove ecosystems (El Hussieny et al., 2021)

Mangrove growth in Mororejo Village is restricted to the edges of fishponds, lacking the formation of extensive localized pockets. This pattern stems from extensive planting activities to maintain the fishpond's physical structure against erosion. Additionally, this situation reflects the inadequacy of rehabilitation efforts to restore mangrove community function according to the coastal ecosystem zonation (Demopoulos et al., 2024; Rahadian et al., 2022). Field observations indicate that planting, particularly of *Rhizophora* species, is often haphazard without considering substrate conditions or appropriate zonation along the shoreline. This practice results in *Rhizophora* seedling mortality due to strong tidal currents. This result is in line with a previous study in Ngombol District, Purworejo, in which the failure of mangrove planting activities was linked to poor planning, plant type incompatibility, and disrupted tidal cycles, highlighting the importance of thorough planning and coordination (Rachmawati et al., 2023).

Field observations revealed mixed mangrove communities in the open zone of Mororejo Village, comprising *A. marina*, *A. officinalis*, *R. apiculate*, *R. stylosa*, and *R. mucronata*. Notably, the massive growth of several *Avicennia* species was observed in areas directly exposed to the open sea. This phenomenon is attributed to the resilience and adaptability of the Avicennia species to high salinity, tides, and wave action (Sudhir et al., 2022). Additionally, Avicennia in Mororejo Village exhibits favorable growth in sandy substrate areas. Behind the open zone, a mixture of true mangroves from the Avicennia and Rhizophora genera coexists with the mangrove associates Leucaena leuccephala and *Talipariti tiliaceum*.

The dominance of *R. mucronata* in Kartikajaya's mangroves likely stems from its easy cultivation, rapid growth, and coastal resilience, making it ideal for planting efforts by various parties. Additionally, *R. mucronata*'s demonstrably effective role in coastal protection further strengthens its dominance within the village's mangrove ecosystem (Widayanti & Firmansyah, 2022). This dominance is further reflected in the importance values, with *R. mucronata* achieving the highest scores at both the tree and seedling stages. *R. stylosa*, on the other hand, is more prevalent at the sapling stage, with a peak importance value. Field observations also reveal a stable mangrove community in Kartikajaya Village with moderate species diversity and even species abundance distribution, without any single dominant species (Table 7).

In Kartikajaya Village, mangroves predominantly thrive on silt-clay substrates inundated by seawater throughout the day. Mangrove zonation in this area is delineated by the distribution of *R. mucronata* and *R. stylosa*, which flourish in riverine areas with clay substrates and high salinity levels resulting from coastal erosion. Avicennia growth zones exhibit silt substrates with minimal inundation and are dominated by large trees estimated to be decades old. Avicennia's adaptability to silt substrates is attributed to pneumatophores, which facilitate gas exchange and oxygen uptake (Srikanth et al., 2016). Furthermore, the terrestrial zone in Kartikajaya Village is characterized by the abundance of *B. gymnorrhiza* species, intentionally planted by residents to mitigate erosion and withstand strong winds.

Observations in Pidodo Wetan Village revealed five mangrove species constituting the ecosystem, including the distinctive *X. moluccensis*, which was not found in other sampling areas. However, the low sapling density is attributed to the mature age of the mangroves, typically around 30 years old, resulting in extensive and robust root systems, large stem diameters, and reduced sapling recruitment. Species diversity is considered moderate for both tree and sapling strata, while seedling diversity is considered low due to the dominance of only two species.

In Pidodo Kulon Village, *R. mucronata* holds the highest importance values at both the tree and seedling stages. Then, *E. agallocha* exhibits the highest importance value at the sapling stage. Notably, *E. agallocha* is exclusively found in Pidodo Kulon Village, likely introduced through planting activities. Furthermore, analysis of the mangrove ecosystem structure reveals that Pidodo Kulon Village possesses a moderate diversity index with low dominance. However, the evenness index indicates that the tree-level mangrove ecosystem is in an unstable and depressed state at the seedling level, where *R. mucronata* is observed to dominate. Field observations indicate that the presence of mature mangrove trees with large diameters and strong root systems suggests slow forest regeneration. Enhancing seedling diversity is crucial for ecosystem rejuvenation, with several best practices identified to improve coastal ecosystem quality. These include hydrological restoration to facilitate seed dispersal and growth (Echeverría-Ávila et al., 2019) and maintaining genetic diversity to prevent bottlenecks and ensure long-term sustainability (Granado et al., 2018).

Field observations revealed that the mangrove ecosystems in Pidodo Wetan and Pidodo Kulon Villages are both situated at the mouth of the Bodri River, an area perpetually inundated by tidal seawater. In Pidodo Wetan, the open zone comprises a community of *A. marina*, *A. officinalis*, *R mucronate*, *R stylosa*, and *X. moluccensis*, thriving on delicate sand substrates. The middle zone is dominated by *R. mucronate*, *R. stylosa*, and *E. agallocha* species, flourishing in an environment characterized by mud substrates and relatively high salinity levels. This study highlights the dominance of the *Rhizophora* genus among the mangrove species encountered at all four sampling sites. The dominance of this genus can be attributed to its adaptability (Sudhir et al., 2022), ease of cultivation (Yoshikai et al., 2021), and the abundance of readily available seedlings compared to other mangrove species (Irawan et al., 2023). Local communities further contribute to its prevalence by collecting seedlings from the natural environment for aquaculture, conservation, and mangrove rehabilitation efforts.

Table 7. Mangrove community structure at the growth/strata level in Mororejo

Spesies	N (Ind)	D (ha)	DR (%/ha)	K (Ind/ha)	KR (%/ha)	F (%)	FR (%)	IVI (%)	H'	E	C
Mororejo											
Tree											
A. marina	44	164.88	37.44	367	25.43	0.58	26.92	89.80	0.36	0.20	0.06
A. officinalis	15	24.51	5.57	125	8.67	0.33	15.38	29.62	0.23	0.13	0.01
R. apiculata	23	43.22	9.82	192	13.29	0.25	11.54	34.65	0.25	0.14	0.02
R. mucronata	38	57.00	12.95	317	21.97	0.50	23.08	57.99	0.32	0.18	0.05
R. stylosa	50	149.48	33.95	417	28.90	0.42	19.23	82.08	0.35	0.20	0.08
T. tiliaceum	3	1.25	0.28	25	1.73	0.08	3.85	5.86	0.08	0.04	0.00
Total	**173**	**440.34**		**1442**		**2.17**			**1.59**	**0.89**	**0.22**
									Mod.	Stable	Low
Sapling											
A. marina	2	0.05	0.39	17	4.08	0.17	18.18	22.65	0.20	0.12	0.00
L. leucocephala	1	0.01	0.05	8	2.04	0.08	9.09	11.18	0.12	0.07	0.00
R. mucronata	33	11.97	90.00	275	67.35	0.33	36.36	193.71	0.28	0.17	0.45
R. stylosa	12	1.26	9.45	100	24.49	0.25	27.27	61.21	0.32	0.20	0.06
T. tiliaceum	1	0.01	0.11	8	2.04	0.08	9.09	11.24	0.12	0.07	0.00
Total	**49**	**13.30**		**408**		**0.92**			**1.04**	**0.65**	**0.51**
									Mod.	Unstable	Mod.
Seedling											
R. apiculata	35			7292	19.66	0.08	9.09	28.75	0.28	0.25	0.04
R. mucronata	106			22083	59.55	0.50	54.55	114.10	0.32	0.29	0.35
R. stylosa	37			7708	20.79	0.33	36.36	57.15	0.36	0.33	0.04
Total	**178**			**37083**		**0.92**			**0.96**	**0.87**	**0.43**
									Low	Stable	Low
Kartikajaya											
Tree											
A. marina	68	252.34	16.07	567	17.85	0.25	15.79	49.71	0.30	0.17	0.03
A. officinalis	13	8.04	0.51	108	3.41	0.08	5.26	9.19	0.11	0.06	0.00
B. gymnorhiza	49	73.11	4.66	408	12.86	0.25	15.79	33.31	0.24	0.13	0.02
R. apiculata	2	0.10	0.01	17	0.52	0.08	5.26	5.79	0.08	0.04	0.00
R. mucronata	157	921.71	58.72	1308	41.21	0.50	31.58	131.50	0.36	0.20	0.17
R. stylosa	92	314.50	20.03	767	24.15	0.42	26.32	70.50	0.34	0.19	0.06
Total	**381**	**1569.80**		**3175**		**1.58**			**1.43**	**0.80**	**0.28**
									Mod.	Stable	Low
Sapling											
A. marina	34	9.74	9.42	283	15.18	0.25	16.67	41.26	0.27	0.15	0.02
A. officinalis	6	0.30	0.29	50	2.68	0.08	5.56	8.52	0.10	0.06	0.00
B. gymnorhiza	43	8.99	8.69	358	19.20	0.25	16.67	44.55	0.28	0.16	0.04
R. apiculata	3	0.09	0.09	25	1.34	0.08	5.56	6.99	0.09	0.05	0.00
R. mucronata	58	34.94	33.78	483	25.89	0.42	27.78	87.45	0.36	0.20	0.07
R. stylosa	80	49.38	47.74	667	35.71	0.42	27.78	111.23	0.37	0.21	0.13
Total	**224**	**103.44**		**1867**		**1.50**			**1.47**	**0.82**	**0.26**
									Mod.	Stable	Low
Seedling											
B. gymnorhiza	12			2500	10.71	0.25	27.27	37.99	0.32	0.29	0.01
R. mucronata	66			13750	58.93	0.33	36.36	95.29	0.35	0.32	0.35
R. stylosa	34			7083	30.36	0.33	36.36	66.72	0.37	0.34	0.09
Total	**112**			**23333**		**0.92**			**1.04**	**0.95**	**0.45**
									Mod.	Stable	Low
Pidodo Wetan											
Tree											
A. marina	13	67.31	8.46	433	18.06	4.33	18.06	44.57	0.28	0.17	0.03
A. officinalis	11	60.13	7.56	367	15.28	3.67	15.28	38.11	0.26	0.16	0.02
R. mucronata	45	666.81	83.80	1500	62.50	15.00	62.50	208.80	0.25	0.16	0.39
R. stylosa	2	1.39	0.18	67	2.78	0.67	2.78	5.73	0.08	0.05	0.00
X. moluccensis	1	0.11	0.01	33	1.39	0.33	1.39	2.79	0.04	0.02	0.00
Total	**72**	**795.75**		**2400**		**24.00**			**0.91**	**0.57**	**0.44**
									Low	Unstable	Low

Spesies	N (Ind)	D (ha)	DR (%/ha)	K (Ind/ha)	KR (%/ha)	F (%)	FR (%)	IVI (%)	H’	E	C
Sapling											
A. marina	2	0.13	29.34	67	33.33	0.67	33.33	96.01	0.36	0.26	0.11
A. officinalis	1	0.06	14.57	33	16.67	0.33	16.67	47.90	0.29	0.21	0.03
R. mucronata	2	0.20	45.85	67	33.33	0.67	33.33	112.51	0.37	0.27	0.11
R. stylosa	1	0.04	10.25	33	16.67	0.33	16.67	43.58	0.28	0.20	0.03
Total	**6**	**0.44**		**200**		**2.00**			**1.3**	**0.94**	**0.28**
									Mod.	Stable	Low
Seedling											
A. marina	11			9167	26.83	0.33	33.33	60.16	0.36	0.52	0.07
R. mucronata	30			25000	73.17	0.67	66.67	139.84	0.25	0.36	0.54
Total	**41**			**34167**		**1.00**			**0.61**	**0.88**	**0.61**
									Low	Stable	Low
Pidodo Kulon											
Tree											
A. alba	29	163.74	8.95	322	14.15	3.22	14.15	37.24	0.26	0.16	0.02
A. marina	27	64.35	3.52	300	13.17	3.00	13.17	29.86	0.23	0.14	0.02
E. agallocha	9	3.36	0.18	100	4.39	1.00	4.39	8.96	0.10	0.06	0.00
R. mucronata	108	1514.56	82.80	1200	52.68	12.00	52.68	188.16	0.29	0.18	0.28
R. stylosa	32	83.18	4.55	356	15.61	3.56	15.61	35.77	0.25	0.16	0.02
Total	**205**	**1829.20**		**2278**		**22.78**			**1.13**	**0.70**	**0.34**
									Mod.	Unstable	Low
Sapling											
A. marina	10	1.40	24.93	111	23.26	1.11	23.26	71.45	0.34	0.25	0.05
E. agallocha	15	2.10	37.36	167	34.88	1.67	34.88	107.13	0.37	0.27	0.12
R. mucronata	13	1.81	32.22	144	30.23	1.44	30.23	92.68	0.36	0.26	0.09
R. stylosa	5	0.31	5.48	56	11.63	0.56	11.63	28.74	0.22	0.16	0.01
Total	**43**	**5.61**		**478**		**4.78**			**1.29**	**0.93**	**0.27**
									Mod.	Stable	Low
Seedling											
R. mucronata	82			911	95.35	0.89	88.89	184.24	0.08	0.12	0.91
R. stylosa	4			44	4.65	0.11	11.11	15.76	0.20	0.29	0.00
Total	**86**			**956**		**1.00**			**0.28**	**0.40**	**0.91**
									Low	Depr.	High

Note: N= number of individuals, D= species dominance (ha), DR= relative dominance (%/ha), K= type density (ind/ha), KR= relative density (%/ha), F= frequency, FR= relative frequency (%), IVI= important value index (%), H= diversity index, E = evenness index; C= dominance index. Source: Primary data from the analysis. Depr = depressed community.

Erosion affects the development of mangrove ecosystems on the coast of Kendal Regency

Alterations in mangrove forest areas are intricately linked to the ongoing erosion and accretion processes along the Kendal Regency coastline. Remote sensing imagery reveals a pattern of extensive erosion occurring on the eastern side of the Bodri River delta and the western site of Ngebum Beach, attributed to a combination of factors (Table 5). These include the protruding topography of the river mouth, which directs waves toward the sea, leading to stronger backwash and shoreline erosion. Furthermore, in Ngebum Beach, the structures protruding into the marine environment, disrupting seabed currents, and increasing the accumulation of destructive wave energy are considered as main factors causing shoreline erosion. Additionally, the low mangrove cover in areas experiencing erosion renders them incapable of mitigating the wave energy potential.

Table 5. The length of coastal erosion in Kendal is based on satellite observation.

Research Site	Observation Period	Erosion length (m)	Effect
Bodri river	2012–2022	100.69	submerging several coastal aquaculture ponds and the mainland.
Ngebum Beach	2008–2015 2015–2022	186.97 60.95	damaging and obliterating community aquaculture ponds

This study's findings corroborate previous research that highlights the significant contribution of protruding marine structures to coastal erosion through the disruption and deflection of ocean currents. This phenomenon, as reported by Irsadi et al. (2022) Has resulted in the erosion of over 5500 Ha of coastal areas in northern Central Java, Indonesia, encompassing areas from Kendal Regency to the coastlines of Semarang City and Demak Regency. This situation is further exacerbated by sea-level rise and anthropogenic activities such as reclamation and mangrove deforestation, which diminish the natural protection afforded to the shoreline. It is crucial to recognize that mangrove ecosystems play a pivotal role in mitigating the detrimental effects of erosion by acting as wave buffers and stabilizing sediments (Ahmad & Fuad, 2018; Bhagarathi & DaSilva, 2024).

Several studies have highlighted the detrimental effects of coastal topographical alterations on mangrove ecosystems. These changes, which deflect waves and ocean currents, lead to erosion and habitat degradation. The associated modifications in oceanographic conditions, such as increased wave energy, salinity changes, altered tidal patterns, and sediment substrate transformations, have been shown to hinder mangrove seedling growth and survival (Nugroho & Magdalena, 2020). A study along Semarang City's coast revealed a 65.5% decline in mangrove density between 2013 and 2022, attributed to erosion and land conversion (Safitri et al., 2023). Furthermore, mangrove restoration activities along the Central Java north coast have been extensive since the 2000s, driven by the environmental degradation caused by large-scale shrimp pond development in the 1990s. Additionally, research has documented a growing ecological awareness among coastal communities following the widespread damage to coastal ecosystems. Active environmental conservationists who regularly engage in mangrove ecosystem conservation activities further support this heightened local awareness. Another research has demonstrated that coastal communities generally recognize the crucial role of mangrove forests in preventing coastal erosion and maintaining ecological balance, which positively correlates with participatory activities in mangrove management (Reciproco et al., 2023).

Field observations and previous research have consistently highlighted that mangrove ecosystem degradation is primarily driven by human activities, often exacerbated by environmental factors. Anthropogenic factors such as deforestation and land conversion for aquaculture and industrial purposes warrant urgent attention from various stakeholders to enhance coastal awareness and conservation efforts (Ellison, 2021; Kumari & Pathak, 2023). While such initiatives have been initiated and implemented across Indonesia's coastline, the extent of participation, activities, and achievement varies, including in Kendal Regency. Nonetheless, these efforts demonstrate a growing awareness and proactive approach towards mangrove ecosystem rehabilitation and coastal erosion prevention (Adriyanti et al., 2023).

This study highlights the imbalance between rehabilitation efforts and environmental challenges, indicating that while mangrove coverage has increased, species diversity remains limited. By focusing on the interactions between land-use changes, rising sea levels, and mangrove rehabilitation, this research provides new insights for evidence-based coastal conservation policies. It develops an integrative monitoring approach using satellite imagery and field validation, uncovers the growth and decline dynamics influenced by natural (erosion, accretion) and human-induced (land conversion, aquaculture) factors, and offers empirical data on *Rhizophora* dominance due to rehabilitation, which may impact long-term biodiversity. The study also provides a foundation for coastal spatial planning that integrates erosion mitigation and mangrove sustainability, raises awareness among communities and stakeholders about mangroves' critical role in climate change adaptation and coastal protection, and proposes community-based and multi-stakeholder rehabilitation policies to ensure sustainable mangrove management.

CONCLUSION

This study reveals that the mangrove ecosystem in Kendal has expanded by 52.21% between 2000 and 2023, with the most significant growth occurring in the Bodri River delta, the Kartikajaya coastline, and Ngebum Beach. Despite this expansion, the ecosystem remains vulnerable to erosion, particularly in areas experiencing coastal topographical changes and high human activity. The identification of 11 mangrove species, with a dominance of Rhizophora, indicates the influence of rehabilitation efforts but also highlights limited natural species diversification. To enhance the resilience of Kendal's mangrove ecosystem and inform future conservation strategies, it is crucial to develop community-based erosion mitigation models, implement integrated conservation planning, and foster multi-stakeholder collaboration.

Future research should explore genetic diversity within mangrove species to assess their adaptation to environmental pressures, employ hydrodynamic modeling to predict erosion and sedimentation patterns, and evaluate the long-term effectiveness of rehabilitation efforts in preventing erosion and enhancing biodiversity. Additionally, integrating blue economy initiatives, such as mangrove-based ecotourism and silvofishery, could support local livelihoods while ensuring sustainable conservation. Strengthening community engagement through participatory conservation programs is also essential for fostering local stewardship and long-term ecosystem sustainability.

ACKNOWLEDGMENT

The authors express deepest gratitude to Lembaga Penelitian dan Pengabdian Masyarakat (LPPM), Universitas Negeri Semarang (UNNES), for funding this research, through Daftar Pelaksana Anggaran (DPA) research scheme, and grant number: 325.12.4/UN37/PPK.10/2023.

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