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Field Study of Deposition and Erosion Patterns Around Pandanus Clusters on Sandy Coasts: a Preliminary Investigation

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ABSTRACT Coastal zones are inherently dynamic, often resulting in long-term cumulative impacts such as erosion, which can potentially escalate into disasters. Discussions regarding nature-based solutions, particularly the utilization of coastal forests, have gained prominence due to their environmental benefits. This paper investigates the role of vegetated coasts in mitigating the effects of wave attacks on land, focusing specifically on Coastal Pandanus species. We conducted a systematic monitoring effort to quantify land changes directly around these species in the field. The southern coast of Java, characterized by significant coastal processes, served as the investigation site. We monitored the changes in the foredunes of eight Pandanus clusters identified along a 1 km stretch of the Pandansari and Samas coasts in the Special Region of Yogyakarta, Indonesia. Our systematic monitoring, conducted biweekly from September to December 2023, involved precise measurements of land elevation, sediment deposition, and erosion around the Pandanus clusters. We utilized manual leveling surveys and installed erosion pins to enhance the precision of our topographic assessments. These monitoring techniques allowed us to thoroughly examine the relationship between Pandanus cluster characteristics and coastal processes. Our findings illuminate the pivotal role of Pandanus clusters in shaping coastal profiles, which depend on cluster area and growth characteristics. Additionally, we underscore key points regarding their success rates, limitations, and future strengthening efforts through the implementation of this nature-based solution. This research contributes to a deeper understanding of the complex interactions between coastal dynamics and vegetative elements, paving the way for informed coastal management strategies in the future.

KEYWORDS Coastal Area; Run-up; Foredunes; Vegetated Coast; Monitoring

1 INTRODUCTION

Coastal erosion stands as a formidable challenge at the intersection of natural forces, human activities, and global dynamics like sea level rise and climate change, relentlessly threatening coastal areas worldwide. This erosion, propelled by forces such as wind, waves, tides, and currents, is compounded by human interventions such as beach sand removal and ill-conceived shoreline structures (Karlsson et al., 2015). The resultant imbalance in material supply and export precipitates morphological shifts along coastlines (Nijamir et al., 2021). Addressing erosion risk through monitoring and assessment is pivotal for integrated coastal management, with emerging techniques like terrestrial video mobile mapping and aerial digital photogrammetry showing promise (Bio et al., 2015).

Anthropogenic activities exacerbate coastal erosion, a stark reality exemplified in locales like Sri Lanka (Begum et al., 2021). Human-induced disruptions in sediment supply, alongside inadequate coastal planning, amplify the challenges posed by the dynamic nature of coastlines (Silva et al., 2014). Efforts to address these issues include classifying contributing factors and proposing community-based indices, utilizing methodologies such as the analytic hierarchy process (Khairuddin et al., 2022). These methodologies aim to prioritize interventions and enhance coastal resilience against erosion. Moreover, the intensification of cyclones, accelerated sea level rise, and increased flooding further exacerbate shoreline retreat and ecological damage in vulnerable regions (Behera et al., 2019). Coastal communities face heightened risks as these environmental stressors interact with existing anthropogenic pressures, necessitating comprehensive mitigation strategies that integrate ecological, engineering, and social dimensions.

Coastal erosion's pace often outstrips land generation, driven in part by human-induced alterations to coastal sediment budgets (Warrick et al., 2019). With global sea levels poised to rise further, coastal erosion management transcends national borders (Fitton et al., 2018). Modern coastal ocean modeling systems offer insights into managing coastal zones by simulating various scenarios (Amoudry and Souza, 2011). Yet, the toll of extreme weather events on coastal communities necessitates deeper empirical inquiry, as evidenced in Bangladesh (Kabi and Khan, 2017).

Given these challenges, coastal vegetation emerges as a green/sustainable alternative in erosion management. Mangroves and salt marshes, prized for their role in mitigating wave actions, currents, and storm surges, offer protection to coastal habitats and adjacent lands (Nguyen et al., 2022). Moreover, they can act as a natural stabilizer and buffer against shoreline edge erosion (Chen et al., 2022; Silliman et al., 2019). These findings underscore the pivotal role of coastal vegetation in erosion mitigation.

Alongside natural solutions like coastal vegetation, innovative approaches such as sustainable coastal development practices and natural coastal protection systems are gaining traction (Herbenita et al., 2022; Yuanita et al., 2020). However, effective management hinges on vulnerability assessments and community engagement (Saravanan et al., 2014; Asmawi and Ibrahim, 2013). Understanding coastal erosion's drivers, coupled with robust monitoring and assessment techniques, is imperative for crafting robust mitigation strategies (Pattipawaej and Hardiyan, 2020).

In this context, this paper investigates the efficacy of coastal Pandanus in mitigating shoreline changes induced by wave dynamics. Leveraging field assessments, we observe visual alterations in coastal land elevation within Pandanus clusters. These findings not only shed light on coastal responses but also fuel discourse on the viability of Pandanus as a preventive measure against coastal damage.

2 COASTAL PANDANUS SPECIES AS A VITAL COMPONENT OF COASTAL ECOSYSTEMS

Pandanus species, notably *Pandanus tectorius*, commonly referred to as Coastal Pandanus or screw pine, are integral components of tropical and subtropical coastal ecosystems (Nguyen et al., 2022). Thriving in sandy soils adjacent to beaches and mangrove forests, Coastal Pandanus exhibits distinctive prop roots and aerial roots, offering stability and fortification against coastal erosion. Its major features, such as long, tough leaves, not only protect salt spray and strong winds prevalent in coastal areas but also hold cultural and culinary significance in their native regions.

Research interest in the taxonomy and distribution of Pandanus species, including *Pandanus tectorius*, underscores their ecological and cultural importance. With around 600 species in the genus, some are endemic to specific regions like Madagascar, India, and New Caledonia, while Pandanus species are revered for their diverse ethnobiological, medicinal, and aromatic properties (Adkar and Bhaskar, 2014; Callmander and Buerki, 2013). For example, *Pandanus amaryllifolius* serves as a spice in Indian coastal regions, while in Java, Indonesia, *Pandanus amaryllifolius Roxb* holds ethnobotanical significance (Wakte et al., 2009; Wardah and Setyowati, 2009). Moreover, the discovery of new species like *Pandanus sermolliana* in Madagascar underscores the ongoing exploration of Pandanus species across diverse coastal regions (Callmander et al., 2008, 2013).

Figure 1 Coastal Pandanus species in Pacitan Bay, East Java

Coastal Pandanus assumes a pivotal role in stabilizing shorelines and fostering wildlife habitats in coastal ecosystems. Its presence not only guards against erosion but also provides nesting grounds for green turtles, thus contributing to biodiversity conservation (Agustika et al., 2020). Recent studies have even hinted at its potential in mitigating tsunami impacts, further underlining its ecological significance (Benazir et al., 2024). Beyond its ecological roles, Coastal Pandanus holds cultural importance, with research delving into its utilization in traditional practices and local communities. However, the implementation of nature-based solutions for natural coastal protection has limitations, especially under extreme conditions such as storms (Feagin et al., 2023; Benazir et al., 2024).

The growth of *Pandanus odorifer* in Teluk Pacitan, East Java, is illustrated in Figure 1. This species, known as *P. odorifer*, is strategically planted alongside other vegetation layer species like *C. equisetifolia* and *A. auriculiformis* for tsunami mitigation purposes in Teluk Pacitan, East Java (Benazir et al., 2024). This image serves as visual evidence of the presence and strategic cultivation of Pandanus in coastal regions, highlighting its role in shoreline protection and ecological resilience.

In essence, Pandanus emerges as a linchpin in coastal ecosystems, bolstering shoreline stability, supporting wildlife habitats, and enriching the cultural fabric of coastal communities. Its resilience in the face of coastal challenges and its multifaceted significance underscore its indispensability in tropical and subtropical coastal regions. However, further research is warranted to unravel the full spectrum of Pandanus species diversity,

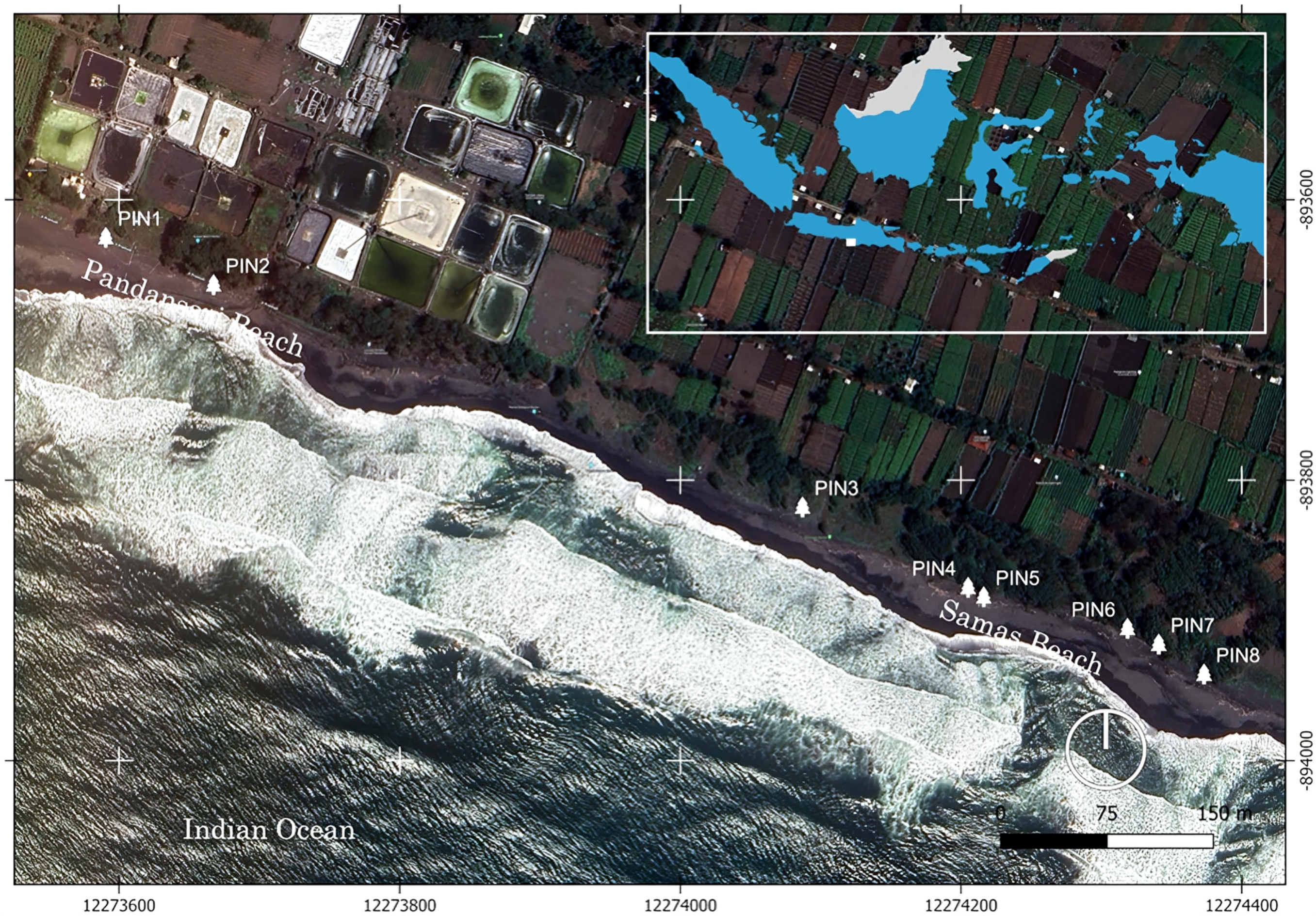

Figure 2 Field monitoring site

Figure 3 Coastal agriculture area in Samas coast, Special Region of Yogyakarta

distribution, and ecological functions in coastal ecosystems.

3 METHODS

3.1 Research Site Profile

The field study encompasses coastal areas along the Southern Coast of Yogyakarta, Indonesia, with a focus on the Pandansari and Samas coasts in Bantul Regency, Yogyakarta Special Region Province, as depicted in Figure 2. Designated for tourism purposes, including nature tourism and culinary tourism, among others, this area embodies a rich tapestry of potential and threats (Yogyakarta, 2019).

The southern coast of Java, particularly in Yogyakarta, presents a dynamic profile marked by seismic vulnerability and the looming threat of tsunamis (Widiyantoro et al., 2020). Despite historical susceptibility to tsunamis (Mulia et al., 2019), the region holds promise for marine resources and economic activities, underscored by throughflow benefits and opportunities for marine-based tourism and agriculture (Sprintall et al., 1999; Palupi et al., 2022). Yet, the area is not without risk, as seismic activities in Java's northern reaches pose a constant threat, accentuating the region's tsunami vulnerability (Fahmi, 2023; Fatchurohman et al., 2022). From a hydro-oceanographic perspective, the southern coast of Java, particularly in the Yogyakarta region, exhibits unique wave characteristics influenced by various oceanographic phenomena. Studies have highlighted the presence of coastally trapped Kelvin waves and mesoscale eddies along the south coast of Java, impacting sea surface chlorophyll-a concentration and mixed layer cooling (Xu et al., 2021;

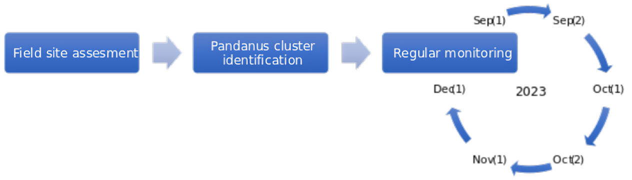

Figure 4 The stage of the field survey

Delman et al., 2018). These waves are associated with the South Java Current and are influenced by factors such as upwelling and wind forcing (Chong et al., 2000). The South Java Current has been identified as a seasonally varying coastal current in this region (Utari et al., 2019). Additionally, significant wave heights along the south coast of Yogyakarta have been noted as a potential source for wave energy conversion systems (Wijaya and Sugita, 2017). The southern waters of Java, facing the Indian Ocean, are recognized for their substantial wave energy potential (Setyawan, 2024).

In the backdrop of these coastal dynamics lies a landscape shaped by agricultural activity (Figure 3). Agriculture in Yogyakarta's coastal areas present a unique blend of opportunities and challenges, intricately combined with climatic vulnerabilities and socio-economic dynamics (Saptutyningsih and Dewanti, 2021). Despite susceptibility to climate-related disasters, the region's agricultural sector holds promise for adaptation and growth, supported by the prospects of agricultural tourism and urban farming (Fatmawati et al., 2021; Gusfarina and Irham, 2019). Moreover, the nexus of social capital, inequality, and environmental factors influence agricultural practices, underscoring the multifaceted nature of agricultural development in coastal Yogyakarta (Saptutyningsih et al., 2020; Wijaya et al., 2021; Susanto et al., 2001). However, challenges such as liquefaction risks and groundwater pollution underscore the imperative for sustainable soil management and environmental stewardship in agricultural activities (Kevin, 2023).

A dynamic interaction between coastal dynamics and agricultural activities characterizes the research site on Yogyakarta's southern coast. This landscape presents a complex socio-economic and environmental setting. Understanding these dynamics is crucial for developing integrated approaches to coastal and agricultural management, addressing challenges, and leveraging opportunities for sustainable development.

3.2 Field Survey Method

The survey methodology deployed in this study aimed to offer a comprehensive appraisal of coastal land dynamics, with a particular focus on deposition or erosion in proximity to Pandanus clusters. The method encompassed three primary stages: field site assessment, Pandanus cluster identification, and regular monitoring, as delineated in Figure 4. Initially, an extensive field site assessment was conducted to identify appropriate monitoring sites along the coastal areas where Pandanus clusters were abundant and where land deposition or erosion was expected. Erosion due to extreme waves has been occurring at this study site for a long time. From 2010 to 2020, the longest erosion distance was approximately 96 meters inland, with the most severe impact occurring in 2022 (Detik, 2023). Factors such as topography, vegetation coverage, shoreline proximity, and historical coastal change data-informed site selection criteria. Subsequently, Pandanus clusters were specifically delineated within the selected monitoring sites through visual inspections of the coastal landscape, homing in on areas densely populated with Pandanus plants or indicative of stabilizing dune systems. For this preliminary study, 8 Pandanus vegetation samples were identified along the Pandansari to Samas coastline, with their locations illustrated in Figure 4.

Following the identification of monitoring sites and Pandanus clusters, regular monitoring commenced, with sessions scheduled biweekly from September to December 2023. Each monitoring session involved detailed measurements to evaluate changes in land elevation, sediment deposition, or erosion around the Pandanus clusters using manual leveling surveys. To bolster the precision of topographic assessments, erosion pins were installed at each Pandanus sample (see Figure 2). These erosion pins, measuring 100 cm in length and featuring a reading scale, were inserted 50 cm into the soil, with the remaining portion above ground level, as depicted in Figure 5. Systematic data recording during monitoring sessions facilitated the tracking of trends over time and the identification of any discernible patterns or anomalies in coastal land dynamics. This survey methodology aimed to provide valuable insights into coastal erosion and deposition processes, particularly for shorter-term assessments essential for informed coastal management and conservation efforts.

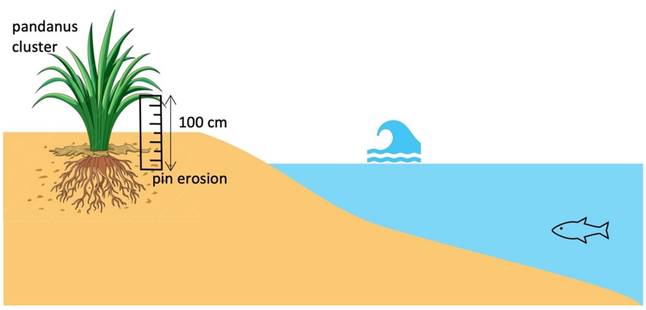

Figure 5 Measuring coastal land changes around Pandanus clusters

4 RESULTS

4.1 Coastal Pandanus Samples

In accordance with previous discussions, 8 clusters of Pandanus samples along the Pandansari and Samas coastline were identified. A survey work spanning 1 km revealed that Pandanus growth exhibited a patchy distribution along the shoreline rather than a continuous spread. These clusters varied in location, with some positioned in the front section of the beach, vulnerable to wave impact. In contrast, others were situated in remote back areas away from daily wave activity. Notably, only one species of Coastal Pandanus, Pandanus tectorius, was found in the vicinity of the site. Coastal pine trees emerged as the predominant vegetation type, strategically planted to enhance agricultural productivity behind the coastal zone. Assessments of these samples shed light on the growth conditions of Pandanus vegetation within the study area. Generally, the age distribution of the vegetation fell predominantly within the early-aged and middle-aged categories, resulting in the absence of extensive clusters observed in other regions, such as Pacitan Bay (see Figure 1). Further details regarding the characteristics of the 8 Pandanus samples (PIN1-PIN8) are presented in Table 1. Although categorized as relatively healthy and in developmental stages, some samples exhibited signs of deterioration due to coastal processes at the site. The health condition of these samples was determined based on signs of damage due to wave exposure on the clusters.

4.2 Short-term Monitoring Results

The results of a brief four-month monitoring effort (September to December 2023), with data readings taken every two weeks, indicate changes in the surface elevation surrounding the Pandanus samples. During the monitoring period, consistent data readings were possible for only 4 out of the 8 samples: PIN1, PIN2 (1) and (2), PIN6, and PIN8. This is due to some samples being affected by extreme wave events in early October, coinciding with the second monitoring session, leading to the loss of erosion PINs installed around those samples. Therefore, the subsequent analysis focuses solely on the findings obtained from these five samples.

Sample PIN1 is administratively situated at Pantai Pandansari, where this cluster grows approximately 50 m from the shoreline (Figure 6). Throughout the monitoring period, the rate of elevation change around the sample was not remarkably significant, with a maximum erosion of -2 mm at the end of September and a deposit of 3 mm at the end of October. The infrequent occurrence of daily wave ranges in this cluster did not considerably alter its ground surface elevation.

Figure 6 Location of sample PIN1 positioned approximately 50 meters from the shoreline

Figure 7 Two erosion PINs were installed within the PIN2 sample cluster

Consequently, it was also observed during the monitoring period that the condition of the Pandanus was quite healthy.

During the second sampling session at PIN2, two erosion PINs were strategically placed within the Pandanus cluster due to preceding coastal processes causing elevation changes. Erosion PIN1 was positioned at the sample's forefront, while erosion PIN2 was inserted at the middle, with a higher ground base elevation, approximately 0.6 m from erosion PIN1, as depicted in Figure 7. This specific cluster, located about 50 m from the shoreline, features a relatively steep coastal profile compared to the PIN1 site. At the forefront of this sample, the vegetation showed signs of wear due to its constant exposure to waves, and the Pandanus roots were visibly exposed due to erosion. Data from erosion PIN1 highlighted the dynamic coastal processes occurring at PIN2. Throughout the monitoring period, erosion rates peaked at -32 mm in early December, while maximum sediment deposition reached 28.5 mm in early November. Similarly, erosion rates were significant in the middle section, recorded by erosion PIN2, reaching -37 mm by late October. Persistent erosion was observed in the middle of this cluster throughout the monitoring period, likely due to an unstable coastal profile resulting from prior erosion at the forefront, leading to sediment depletion upon wave impact.

Table 1. Sample of Pandanus tectorius in field location

No.	Sample	Height (cm)	Width (cm)	Dimension (cm) and remarks	Site photo
1	PIN-1	150	400	Circumference of the lower trunk: 39 Circumference of the upper trunk: 34 Circumference of the branch stem: 20 Circumference of the roots: 18 and 24 Mature-aged, healthy	
2	PIN-2 (1) & (2)	150	590	Circumference of the lower trunk: 23 Circumference of the upper trunk: 17 Circumference of the branch stem: 12 Circumference of the roots: 15 Early-stage, healthy, the front (large) Pandanus has experienced erosion, with some branches dead	
3	PIN-3	105	435	- Early-stage, healthy	
4	PIN-4	180	400	- Middle-aged, healthy	
5	PIN-5	190	400	Circumference of the lower trunk: 43 Circumference of the upper trunk: 19 Circumference of the branch stem: 20-38 Mature-aged and unhealthy, the front section is showing signs of damage due to wave exposure, with visible erosion as well.	
6	PIN-6	200	300	- Mature-aged, healthy	
7	PIN-7	250	685	- Early-stage, healthy, the front part is beginning to be affected by waves, but its overall condition is still excellent.	
8	PIN-8	136	285	- Early-stage and mature-aged, healthy, the front section is showing signs of damage due to wave exposure, with visible erosion as well.	

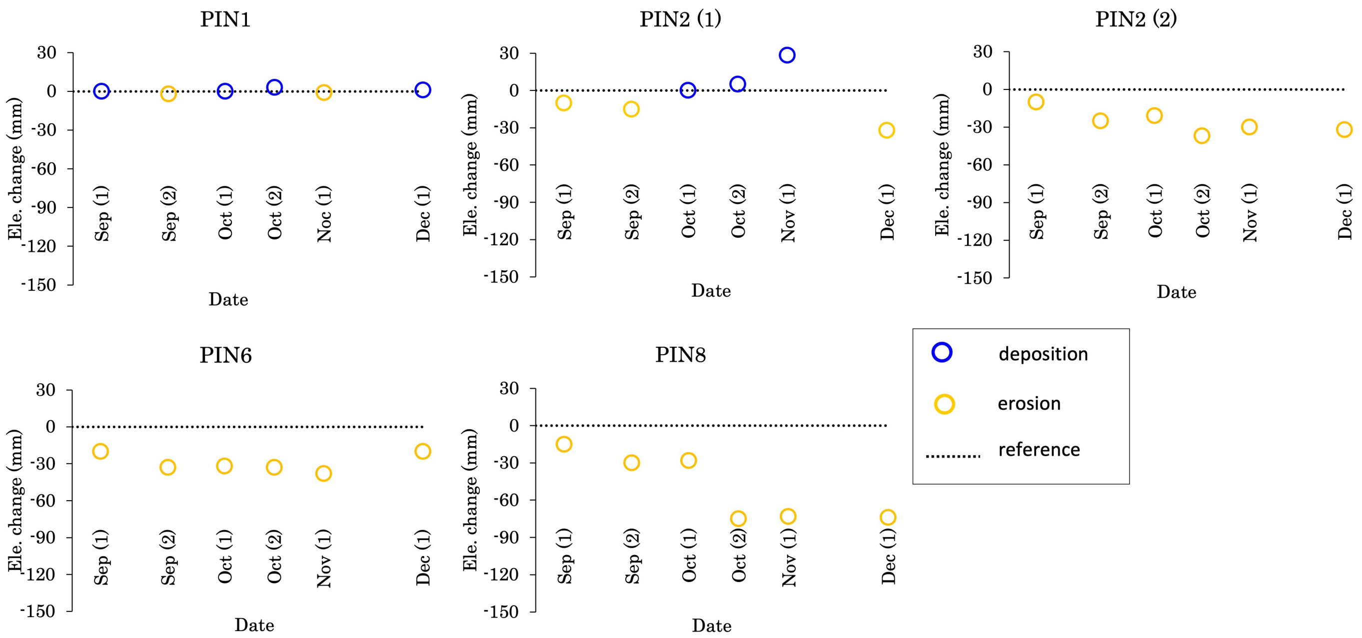

Figure 8 Changes in elevation were recorded for four samples of Pandanus clusters during short-term monitoring

PIN6, situated at Pantai Samas along with PIN7, exhibited satisfactory conditions with vegetation of moderate age, as delineated in Table 1. Throughout the monitoring period, the vegetation's physical health appeared robust, notwithstanding observed fluctuations in base elevation signaling erosion within this sample. Monitoring outcomes unveiled surface elevation alterations surrounding the cluster ranging between -20 and -38 mm.

Similarly, PIN7 underwent erosion throughout the monitoring phase. This cluster had been subjected to constant wave impact before monitoring initiation, leading to root and stem exposure due to wave interaction. Predominantly, erosion occurred within this sample due to coastal processes, with the highest erosion recorded among the four samples, reaching -74 mm.

Consequently, among the four samples observed during local coastal process assessments around the Pandanus clusters, terrain surface changes were apparent. The findings pointed towards a trend of sediment loss, primarily erosion rather than deposition. These alterations predominantly manifested at the forefront of the Pandanus clusters, where susceptibility to wave action was highest. A comprehensive overview of the brief monitoring results for local coastal processes is presented in Figure 8.

5 DISCUSSION

The results of our short-term assessment reveal distinct responses in coastal processes among the sampled areas. While our field monitoring findings offer initial insights, the relationship between age and coastal processes remains constrained, necessitating a deeper exploration of additional parameters, notably the role of hydrodynamic wave dynamics. Nevertheless, the growth and density of Coastal Pandanus vegetation emerge as critical components in coastal protection strategies. Understanding the growth patterns and density of Pandanus clusters along the coastline is crucial for effective and robust coastal management. External/additional factors such as exposure to wave action and soil conditions influence the distribution of Pandanus clusters (Nepf, 1999). The age of Pandanus clusters directly impacts their size and density, thus affecting their effectiveness in providing coastal protection. Early-aged and middle-aged clusters may not offer optimal protection, highlighting the importance of promoting optimal cluster growth (Tanaka, 2009).

Strategic selection of planting sites is essential for maximizing the efficacy of Pandanus as coastal barriers. Factors such as proximity to the shoreline, soil composition, wave exposure, and existing vegetation cover must be carefully evaluated (Tanaka et al., 2006). In our study, Pandanus clusters mainly grow in the foredune area, placing them in direct interaction with waves, especially during extreme conditions. Direct damage from extreme wave action was observed, particularly in sample PIN5 (see Figure 9). Pandanus species' density expansion heavily relies on their age, with growth rate significantly increasing as they mature. Hence, this species is more suitable for planting as a secondary layer or interspersed among coastal pine species. Strategic selection of planting sites can greatly enhance the ability of Pandanus clusters to provide coastal protection and vital ecosystem services. Fur-

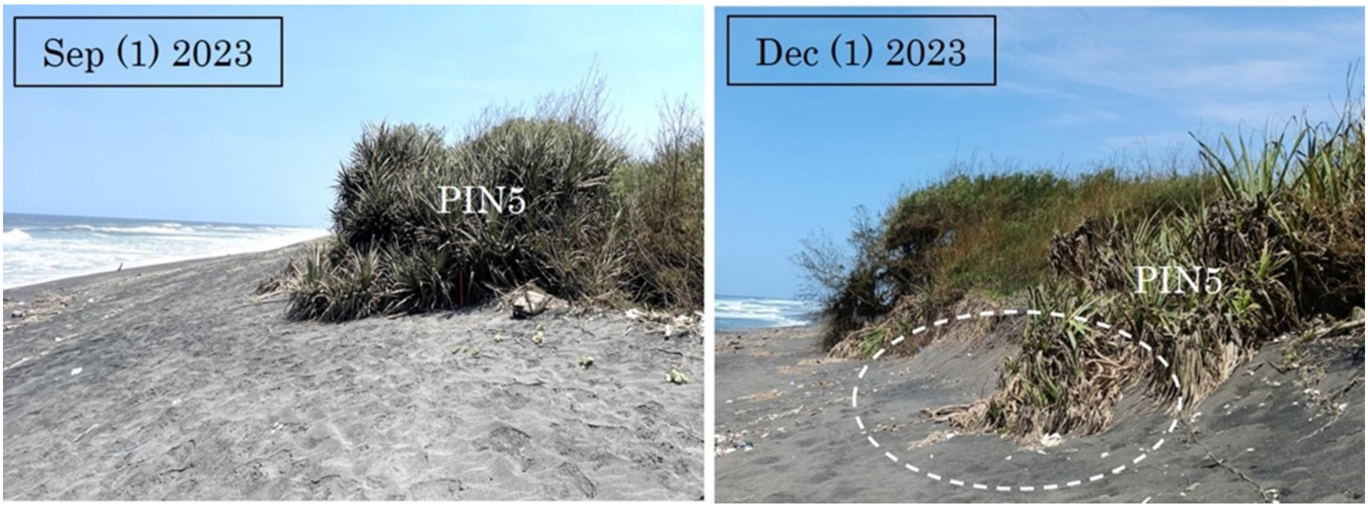

Figure 9 Coastal sediment loss is clearly evident in front of sample PIN5

thermore, the management, protection, and rehabilitation of beach forests are crucial for maximizing their potential as climate change mitigators and for coastal protection (Cañeda et al., 2022).

Regular monitoring of coastal dynamics and the health of Pandanus clusters is paramount for making well-informed decisions in coastal management. Parameters such as changes in elevation, sediment deposition, and indicators of vegetation health are routinely measured during monitoring efforts (Zhang et al., 2018). This continuous monitoring not only aids in identifying trends but also facilitates timely interventions to address coastal erosion and uphold ecosystem resilience. However, the involvement of local communities in the preservation and reforestation of coastal forests is a critical factor. The lack of community engagement poses a significant challenge to vegetation bioshield projects. To tackle these challenges effectively, there is a pressing need for a comprehensive inventory of indigenous species, policy reforms to support their conservation and management, and rigorous enforcement of environmental regulations (Athikalam and Vaideeswaran, 2022). In areas like Pandansari and Samas coasts, where local communities utilize coastal areas for livelihood purposes such as coastal farming, these communities can play a vital role in preserving coastal vegetation to support their agricultural production sector. This includes the preservation and cultivation of species like Pandanus and coastal pine, which are present in the field.

The study offers valuable insights into the dynamics of coastal processes and their impact on Pandanus clusters along the Pantai Pandansari and Samas coasts. However, several limitations should be acknowledged. Firstly, the short-term monitoring period spanning four months may not fully capture the seasonal variations and long-term trends in coastal dynamics, particularly those influenced by the west and east monsoon seasons. Extending the monitoring duration to encompass multiple seasons would provide a more comprehensive understanding of the dynamic nature of coastal processes. Secondly, while manual field surveys were employed to assess changes in surface elevation, the accuracy of measurements could be improved with the incorporation of topographic GPS technology. Such enhancements would ensure more precise elevation data and enhance the reliability of the findings. Additionally, the study focused solely on monitoring changes in elevation and Pandanus health without considering underlying hydrodynamic processes such as wave dynamics, currents, and tides. Future research should integrate hydrodynamic studies to elucidate the complex interactions between these factors and their influence on coastal erosion and deposition dynamics, thereby advancing our understanding of coastal ecosystem dynamics and informing more effective management strategies.

CONCLUSION

In summary, this study presents the intricate connection between coastal dynamics and vegetative elements, particularly emphasizing the role of Coastal Pandanus species in mitigating wave impacts along the Pandansari and Samas coastline. Through systematic monitoring and analysis, valuable insights into Pandanus cluster distribution, growth characteristics, and responses to coastal processes were gained. Our findings underscore the importance of considering factors like cluster age, density, and location in coastal management strategies. Despite limitations such as a short monitoring period and lack of hydrodynamic process analysis, the study provides a basis for future inquiries. Extending monitoring durations, integrating advanced measurement technologies, and including hydrodynamic studies can enrich our understanding of coastal dynamics and gain more effective management practices. Moreover, community involvement emerges as crucial for coastal forest preservation and reforestation, highlighting the necessity for stakeholder engagement and policy reforms to support conservation efforts. Harnessing indigenous knowledge and implementing nature-based solutions like Pandanus clusters can contribute to sustainable coastal management and resilience against erosion and disasters. Ultimately, this study adds to the growing body of knowledge on coastal dynamics and vegetative elements, offering insights for informed decision-making and sustainable management strategies amid ongoing environmental challenges.

DISCLAIMER

The authors declare no conflict of interest.

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