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Assessment of Mangrove Seedling Growth Performance in a Rehabilitated Coastal Area in Lantebung, Makassar

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ABSTRACT

Mangrove rehabilitation is vital for maintaining coastal ecosystem integrity, mitigating shoreline erosion, and supporting community resilience, particularly in urban and peri-urban areas. This study assessed the survival, growth, and leaf development of mangrove seedlings in a rehabilitated coastal area in Lantebung, Makassar City, aiming to evaluate the effectiveness of long-term restoration interventions. Six plots with diffrent planting densities and environmental conditions were established, and systematic monitoring was conducted monthly from December 2024 to February 2025. Seedling survival rates were calculated, while height and leaf production were measured on 10–15% of randomly selected seedlings per plot. Protective measures, including bamboo-framed beds (Guludan) and bamboo-based wave breakers, were implemented to reduce hydrodynamic stress and to prevent seedling displacement. Results showed substantial variation among plots, with Plot B1 achieving the highest survival rate (83.85%), growth rate (254.97%), and mean leaf count (28.57 leaves per seedling). *Rhizophora apiculata* performed the best overall, indicating its high suitability for rehabilitation in similar coastal environments. Plots exposed to stronger tidal currents or lacking sufficient maintenance exhibited high mortality, emphasizing the importance of site-specific management and adaptive interventions. These findings demonstrate that combining engineering solutions, careful planting strategies, and continuous monitoring is essential to optimizing mangrove restoration success. The study provides evidence-based recommendations for improving rehabilitation practices, enhancing coastal ecosystem resilience, and supporting sustainable management in urbanized coastal areas.

INTRODUCTION

Mangrove forests are unique coastal ecosystems that thrive in saline, tidal environments. They provide essential ecological services, including coastal protection, carbon sequestration, and habitats for diverse marine organisms **(Choudhary *et al.*, 2024)**. Indonesia harbors the world's most extensive mangrove coverage; however, these ecosystems are increasingly threatened by anthropogenic activities and climate change,

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leading to significant degradation. Recent studies indicate that mangrove forests in Indonesia have experienced the most extensive deforestation globally, primarily due to the expansion of aquaculture and oil palm plantations **(Ramadhani, 2022; Yamamoto, 2023)**.

The Lantebung mangrove area in Makassar, South Sulawesi, exemplifies these challenges. Despite restoration efforts initiated in 2010, the region has experienced substantial mangrove loss **(Rini *et al.*, 2018)**. While community-based initiatives have been implemented, the effectiveness of these efforts remains uncertain due to insufficient monitoring, inadequate engagement of local stakeholders, and environmental stressors such as tidal inundation and sediment compaction **(Akram *et al.*, 2024)**. The survival of planted seedlings is often low, which undermines the success of rehabilitation program.

Mangrove seedling planting is a primary strategy to restore degraded forests and expand mangrove coverage, promoting biodiversity. However, global rehabilitation efforts frequently fail when planting practices are oversimplified and do not adhere to silvicultural principles **(Brown *et al.*, 2014)**. Seedlings are sometimes forced to grow on tidal mudflats below the average sea level, where naturally dispersed propagules would not survive **(Shih *et al.*, 2022)**. Another major challenge is the limited participation of local communities in maintaining mangrove ecosystems. Effective restoration requires structured management procedures and active stakeholder involvement to monitor seedling growth and ensure long-term survival **(Damastuti *et al.*, 2023)**.

Successful mangrove rehabilitation goes beyond merely planting trees; it represents a long-term investment to protect the environment, mitigate climate change, and enhance the welfare of coastal communities **(Sunkur *et al.*, 2023)**. Restoration activities can generate ecological, economic, and social benefits by considering the biological characteristics of mangrove species, associated fauna, and local hydrology **(Mohan *et al.*, 2025)**. Therefore, community participation, ecological knowledge, and integrated management practices are fundamental to achieving sustainable outcomes.

Despite numerous studies on mangrove restoration **(Sasmito *et al.*, 2022; Damastuti *et al.*, 2023; UNEP, 2023)**, critical gaps remain. Most research focuses on large-scale planting programs or general ecological outcomes, while few studies quantitatively evaluate seedlings survival and growth rates in long-term rehabilitated coastal areas. Furthermore, limited research integrates biological characteristics, local hydrology, and community participation in a single framework to assess restoration success. This represents a significant knowledge gap that impedes optimizing restoration strategies in urban coastal environments like Lantebung.

This study addressed these gaps by evaluating mangrove seedlings growth performance in the rehabilitated coastal area of Lantebung, Makassar. Specifically, the objectives were: (1) to assess the survival rates of mangrove seedlings and (2) to measure their growth rates over time. This research provides novel insights into the effectiveness of long-term rehabilitation programs, offering evidence-based recommendations for improving mangrove restoration practices in urban and peri-urban coastal areas.

Mangrove rehabilitation is a complex and multidimensional task requiring scientific knowledge, strategic planning, and stakeholder collaboration. By assessing seedling survival and growth in Lantebung, this study contributes to closing the research gap in long-term, site-specific mangrove restoration, supporting sustainable coastal ecosystem management, and enhancing community resilience.

MATERIALS AND METHODS

1. Time and study location

This study was conducted in six designated plots within the rehabilitated mangrove area in Lantebung Village, Bira Subdistrict, Makassar City, South Sulawesi (Fig. 1), in collaboration with the Indonesian Marine Conservation Foundation (YKL-Indonesia). The plots were selected to represent the restoration site's varying planting densities and environmental conditions. Data were collected from July 2024 to February 2025.

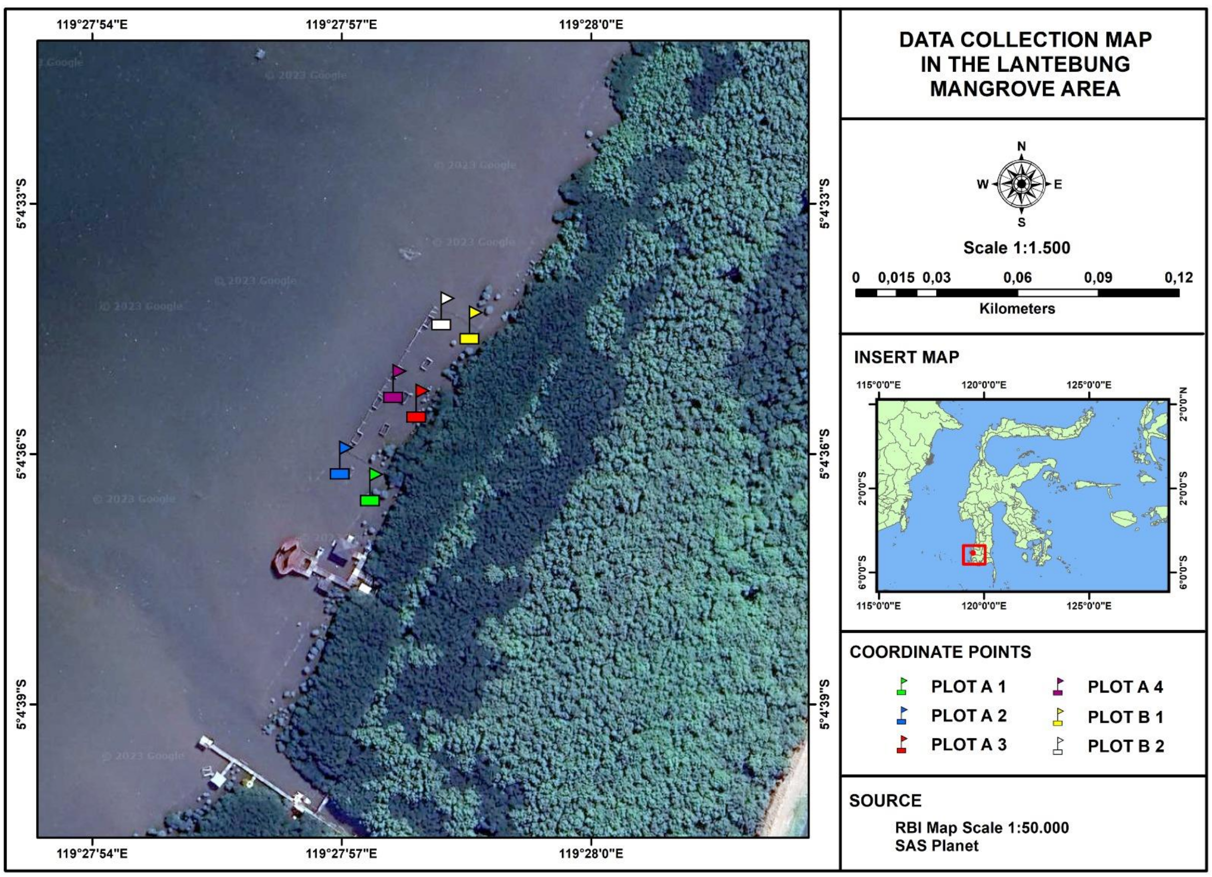

Fig. 1. Study site in Lantebung Village, Bira Subdistrict, Makassar City

2. Materials and equipment

The materials and equipment used for fieldwork and data collection are summarized in Table (1). They were essential for monitoring mangrove seedling survival, growth, and documentation.

Table 1. Materials and equipment used

No	Equipment/Material	Function
1	Stationery	Recording observation data
2	Measuring tape	Measuring seedling height
3	Werpack	Protective gear for fieldwork
4	Boots	Foot protection in muddy areas
5	Camera	Field documentation
6	Manual counter	Counting leaves
7	Waterproof case	Protecting devices from water and mud
8	Clipboard	Writing surface for field data sheets
9	Laptop	Data processing
10	Cable ties	Marking individual seedlings

3. Mangrove rehabilitation procedure

a) Seedling planting

The species planted in the same pot included *Rhizophora mucronata* and *R. stylosa* (Fig. 2). Seedlings were collected from naturally fallen propagules by local communities and planted in the field starting in July during low tide for easier anchoring. Planting patterns varied, including pure, clumped, and random arrangements, with spacing between seedlings ranging from 0.6 to 1m.

Fig. 2. Planting mangrove seedlings in Lantebung

b) Wave breaker installation

A bamboo-based wave breaker (Hybrid Engineering/Seawall) was installed along the coast to reduce wave impact and protect the newly planted seedlings (Fig. 3). A total of 500 bamboo units, spanning 63 meters, were used to shield the seedlings from strong waves.

Fig. 3. A bamboo-based wave breaker (Seawall)

c) Bed or guludan construction

Seedlings were planted within bamboo-framed beds (Guludan, Fig. 4) to prevent displacement by tidal currents. The plots were organized into clumps with different planting densities, such as dense 0.25 × 0.25 m, medium 0.5 × 0.5 m, and sparse 1 × 1 m. This method has proven effective in flooded or waterlogged areas **(Kusmana *et al.*, 2015)**.

Fig. 4. Guludan construction

4. Data collection

Following the rehabilitation and planting of mangrove seedlings, a systematic monitoring program was conducted to evaluate seedling survival, growth, and leaf development. Monthly monitoring was carried out from December 2024 to February 2025, with each session spanning two consecutive days (25–26 of each month). This approach ensured consistent and regular data collection to capture early growth trends and survival rates.

a) Team and task assignment

Before fieldwork, the monitoring team, consisting of 3–4 trained personnel, prepared the necessary equipment, including waterproof clothing (wetsuit), boots, measuring tapes, manual counters for leaves, waterproof cases for electronic devices, clipboards, and marking materials such as cable ties. Each team member was assigned specific roles to optimize workflow efficiency: one measured seedling height, another counted leaves, and a third recorded survival data. All members assisted with documentation and plot management.

b) Monitoring procedure

Data were collected from six sampling plots (A1, A2, A3, A4, B1, and B2), each measuring 5 × 5 m. The number of plots for category A (four) and B (two) followed the availability of rehabilitated stands, since pattern A was more frequently found in the field. In contrast, pattern B was limited to only two suitable patches. All seedlings were assessed for survival within each plot, with living and dead seedlings counted to calculate the survival rate. A subset of 15 representative seedlings per plot was selected, marked with cable ties, and measured for height to assess growth. Leaf number per seedling was also recorded manually, with 10–15% of randomly selected seedlings sampled per plot to estimate average foliar development. Additionally, the monthly distribution of natural recruitment was assessed by counting newly emerged seedlings within each plot during the regular monitoring surveys, and distinguishing them from planted individuals based on size and position.

The monitoring process was carefully standardized to minimize disturbance to the seedlings. Seedlings were measured during low tide periods whenever possible to facilitate access and reduce the risk of trampling or sediment disturbance. All measurements were regularly recorded on data sheets and later transferred to a digital database for analysis. Photographic documentation was taken for each plot to confirm seedling condition and support visual observation of growth trends. Following this structured, continuous monitoring protocol, the study captured comprehensive data on seedling survival, height increase, and leaf production over the three months. This allowed for an integrated assessment of the effectiveness of rehabilitation techniques, including wave breaker protection, bed (bundle) construction, and varying planting patterns, in supporting mangrove establishment and growth.

5. Data analysis

a) Seedling survival rate

The survival of mangrove seedlings was assessed by calculating the percentage of living seedlings in each sampling plot. The survival rate (SR) was calculated according to the formula specified in Peraturan Menteri Kehutanan No. P.70 Tahun 2008 and following **Irwanto *et al.* (2024)**:

$$Survival\ Rate\ (SR\ \%) = \frac{JTH}{JTT} \times 100\ \%$$

Where, *SR* is the survival rate in percent, *JTH* refers to the number of living seedlings, and *JTT* is the total number of seedlings planted. Seedling survival was classified as successful (SR ≥ 70%) and less successful (SR < 70%). This metric provides a quantitative measure of the effectiveness of the rehabilitation efforts and allows comparison among different plots and planting methods.

b) Growth rate (seedling height)

Seedling growth was evaluated based on height increment over time. The growth rate (GR) was calculated using the following formula **(Irwanto *et al.*, 2024)**:

$$\mathrm{GR}\ (\%) = \frac{H_2 - H_1}{H_1} \times 100$$

Where, GR is the growth rate of seedling height (%), H_1 reflects the initial seedling height at the time of planting (cm), and H_2 represents seedling height at the time of monitoring (cm). The average growth rate for each plot was calculated to evaluate overall seedling performance and to compare growth under different planting patterns and protective measures (e.g., wave breakers and guludan).

c) Leaf count

Leaf development was assessed by manually counting the number of leaves on randomly selected seedlings. Approximately 10–15% of seedlings in each plot were sampled to estimate average foliar development **(Islami *et al.*, 2022)**. The mean number of leaves per plot was calculated using the following formula **(Makaruku & Aliman, 2019)**:

$$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n}$$

Where, X is the mean number of leaves per seedling, X_i shows a leaf count of the i-th sampled seedling, and n is the total number of sampled seedlings. The combination of survival rate, height growth, and leaf count provides a comprehensive assessment of the performance and health of mangrove seedlings in the rehabilitated area.

All data analyses were performed using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA), which was used to operate the formulas and calculate the required values.

RESULTS AND DISCUSSIONS

1. Surviival rate

The survival rate of mangrove seedlings across the six plots in the Lantebung rehabilitation site exhibited considerable variation over the eight-month monitoring period. As shown in Fig. (5) and Table (3), Plot B1 consistently demonstrated the highest survival rate, maintaining 83.85% from July 2024 to February 2025, indicating the successful establishment of seedlings under the given environmental and management conditions. In contrast, Plots A1, A2, A3, A4, and B2 recorded markedly lower survival rates, with final percentages of 0.77, 33.51, 48.82, 2.03, and 1.96%, respectively, suggesting limited success in seedling establishment. The initial number of seedlings per plot (Table 2) ranged from 102 in B2 to 191 in A2. However, higher initial density did not necessarily translate into higher survival, as survival outcomes were more strongly affected by site-specific factors such as tidal inundation frequency, sediment stability, shading, and maintenance intensity, rather than planting density alone **(Gijsman *et al.*, 2021)**.

Table 2. Total number of seedlings per plot at initial planting

No.	Plot	Total Number of Seedlings (Initial)
1	A1	130
2	A2	191
3	A3	127
4	A4	148
5	B1	130
6	B2	102

Table 3. Survival rate (%) of mangrove seedlings in Lantebung from July 2024 to February 2025

Plot	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
A1	20.00	20.00	18.46	18.46	12.31	9.23	6.15	0.77
A2	32.46	31.94	30.89	30.89	30.89	29.84	28.8	33.51
A3	59.06	57.48	55.91	55.91	55.91	55.91	55.91	48.82
A4	12.16	12.16	12.16	12.16	11.49	10.18	6.08	2.03
B1	84.62	83.85	83.85	83.85	83.85	83.85	83.85	83.85
B2	42.16	38.24	38.24	38.24	36.27	11.76	6.86	1.96

The notable differences in survival among plots can be attributed to a combination of abiotic and biotic factors. For instance, plots exposed to stronger tidal currents and wave action, such as A1, A4, and B2, exhibited high seedling mortality, consistent with previous studies showing that hydrodynamic stress is a major limiting factor for early mangrove establishment **(Cannon *et al.*, 2020)**. Furthermore, heavy rainfall events have been reported in previous studies as potential drivers of seedling mortality through waterlogging and seedling uprooting **(Van Hespen *et al.*, 2023)**. Although no local precipitation data were collected during our monitoring period, such processes cannot be ruled out as contributing factors in the observed mortality.

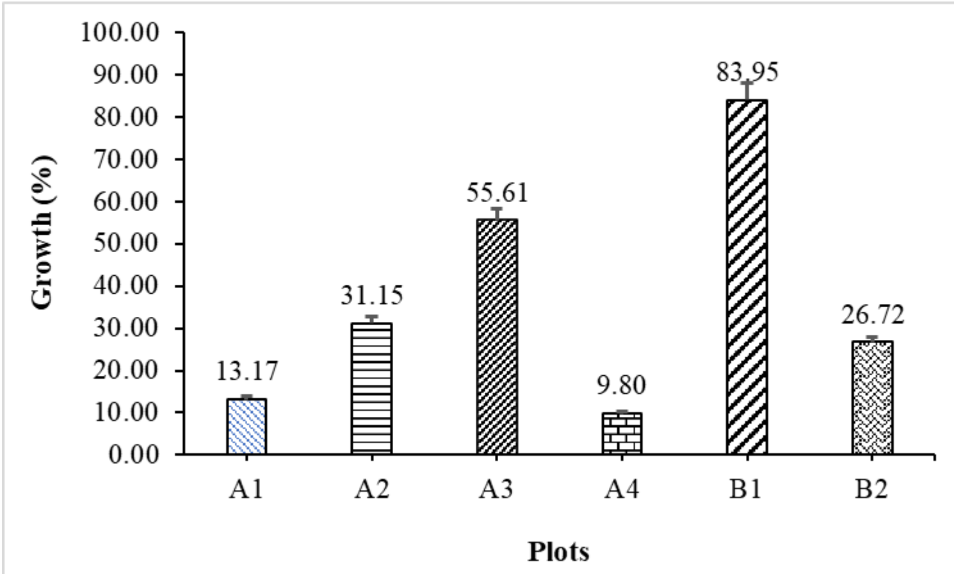

Fig. 5. Mean percentage of mangrove seedling growth

Management interventions, including using bamboo-framed beds (Guludan) and wave-breaking structures, were applied in several plots. In B1, where these measures were combined with favorable site conditions, they likely contributed to the particularly high survival observed. These measures reduced physical stress from tidal flows and protected seedlings from displacement, emphasizing the critical role of site-specific engineering solutions in mangrove rehabilitation **(Benazir *et al.,* 2024)**. Additionally, plots with lower survival rates appeared to have less effective protection and/or received less consistent maintenance compared to B1, which may have contributed to the observed differences in survival. This suggesting that post-planting care and regular monitoring are crucial for ensuring seedling persistence. In this context, community involvement plays a key role by providing the labor and local knowledge necessary for activities such as maintenance of protective structures, replanting of failed seedlings, and routine site monitoring, in line with findings from **Preece *et al.* (2023)**, who highlighted the importance of community involvement and active management in mangrove restoration success.

The observed patterns also underscore the role of natural recruitment in enhancing plot-level survival. In plots with higher survival rates, occasional recruitment of new seedlings contributed to maintaining overall vegetative cover. Recruitment was recorded during the same monitoring surveys used for survival counts, by noting naturally established seedlings within each 5 × 5 m plot. The occurrence was not uniform across plots, likely due to differences in propagule supply, hydrodynamic conditions, and microhabitat suitability, which influence natural regeneration **(Loureiro *et al.,* 2021)**. However, the near-total mortality in some plots indicates that seedling losses can be substantial without sufficient protective measures and hydrological management, which may undermine the long-term objectives of mangrove restoration.

The survival rate data from Lantebung illustrate that while rehabilitation efforts can achieve high success under optimal conditions, variability in environmental exposure (e.g., tidal inundation, sediment stability, and shading) and management practices (e.g., frequency of maintenance and effectiveness of protective structures) management practices significantly affects seedling outcomes. These results highlight the need to integrate hydrological, ecological, and engineering considerations into rehabilitation design and implement continuous monitoring and adaptive management to enhance overall success in mangrove restoration projects.

2. Growth rate

The growth performance of mangrove seedlings in the rehabilitated coastal area of Lantebung, Makassar, was monitored across eight consecutive months, revealing substantial variation among the six experimental plots (A1–A4, B1–B2). Seedling heights was measured at the time of planting in July 2024, and the values presented represent the mean initial height of seedlings within each plot, ranging from 23.7cm in plot B2 to 57.7cm in plot A2, indicating heterogeneity in starting conditions (Table 4).

Table 4. Initial height of mangrove seedlings at the time of planting

No.	Plot	Initial Seedling Height (cm)
1	A1	37.3
2	A2	57.7
3	A3	41.1
4	A4	39.7
5	B1	27.4
6	B2	23.7

Over the monitoring period, the relative growth rate (%), exhibited a progressive increase within each plot (Fig. 6). While growth trajectories were consistent in showing upward trends, the magnitude and pace of increase varied across plots, underscoring that comparisons are more appropriately interpreted in terms of temporal changes within plots rather than direct cross-plot mean differences. Plots B1 and B2 consistently demonstrated the highest growth percentages, with mean growth rates peaking at 254.97 % and 268.74 %, respectively, by February. In contrast, plots in group A exhibited more moderate increases, with growth rates ranging from 78.65 % (A2) to 146.39 % (A4).

Table 5. Growth rate of mangrove seedlings

Plots	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
A1	75.15	100.19	121.10	122.33	123.06	153.73	160.40	154.69
A2	53.33	57.02	57.71	71.58	75.16	93.99	107.40	113.05
A3	97.40	116.23	131.14	133.75	146.55	159.00	173.97	192.63
A4	113.60	123.35	125.52	137.78	143.32	164.99	177.91	184.63
B1	201.09	208.03	220.44	244.89	248.18	294.16	310.58	312.41
B2	226.71	232.07	239.24	278.48	282.15	289.58	305.06	296.62

Table 6. Monthly increase in mangrove seedling growth (%). 0% indicates no measurable growth that month

Plots	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
A1	0	25.04	20.91	1.23	0.73	30.67	6.67	0
A2	0	3.69	0.69	13.87	3.58	18.83	13.41	5.65
A3	0	18.83	14.91	2.61	12.8	12.45	14.97	18.66
A4	0	9.75	2.17	12.26	5.54	21.67	12.92	6.73
B1	0	6.93	12.41	24.45	3.29	45.98	16.42	1.82
B2	0	5.36	7.17	39.24	3.67	7.43	15.48	0

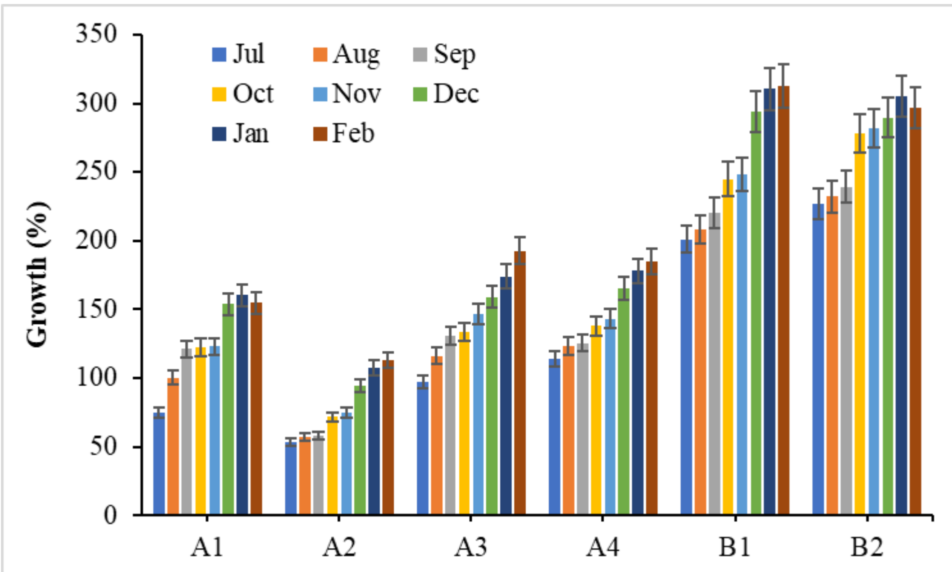

Fig. 6. Mean of seedling growth rate (%)

The monthly increment data (Table 6) provide further insight into temporal growth patterns. Early months (July–September) showed modest growth across all plots, followed by a notable acceleration from October to January. While all plots exhibited this general seasonal trend, the magnitude of growth differed substantially. For instance, plots B1 and B2 showed the highest increases, with B1 experiencing a sharp surge of 45.98% in December, likely reflecting favorable micro-environmental conditions and management support. In contrast, plots such as A2 and A4 displayed more gradual increments, suggesting that despite similar overall seasonal influences, differences in hydrological exposure and maintenance intensity shaped the distinct growth outcomes. Conversely, plot A2 maintained a relatively slow but steady growth, indicating potential limitations in site-specific factors such as soil salinity, nutrient availability, or hydrological dynamics.

These findings align with previous studies emphasizing the influence of initial seedling size and site conditions on mangrove growth trajectories. For instance, **Ardli *et al.* (2024)** demonstrated that seedling of smaller size often exhibit higher relative growth rates but may be more sensitive to environmental stress. In contrast, larger seedlings tend to have more established root systems that confer stability but moderate relative growth. However, the observed differences among plots (e.g., A1 and A3 compared with B1) cannot be explained solely by initial seedling size or planting density. Despite having comparable or slightly lower seedling numbers, B1 showed higher growth rates, suggesting that micro-environmental conditions (e.g., reduced wave exposure) and additional protection measures played a stronger role than density effects in driving growth outcomes. Furthermore, studies in rehabilitated mangrove forests highlight that soil fertility, tidal inundation frequency, and species-specific adaptive traits critically determine growth performance **(Proffitt & Travis, 2010)**. In this study, soil fertility was not quantitatively assessed; thus, it is considered here as a potential explanatory factor based on established literature rather than as an empirical variable. The superior growth observed in B plots may be attributable to optimized site conditions or species adaptation, particularly differences in hydrological exposure, sediment stability, and protection from wave energy, which together shape survival and competitive advantage under the prevailing environmental conditions.

This finding suggests that rehabilitation efforts at Lantebung yield positive outcomes, particularly in plots with favorable environmental and ecological conditions. Nonetheless, the variability between plots underscores the importance of site-specific management interventions to maximize mangrove restoration success, including targeted soil amendments, hydrological regulation, and species selection strategies informed by local ecological characteristics.

3. Seedlings leaf count

The monthly leaf count of mangrove seedlings across the six plots exhibited notable variation over the monitoring period from July to February. Plot B1 consistently recorded the highest mean leaf count per seedling (28.57 leaves), followed by A3 (25.03 leaves) and A2 (23.09 leaves), whereas plots A1 (17.73 leaves) and A4 (18.94 leaves) showed relatively lower growth performance (Table 7). The observed leaf increment patterns indicate a general increase from July, peaking around October and November, before declining in the subsequent months, particularly in January and February. This trend is aligned with seasonal growth responses influenced by environmental factors such as rainfall, tidal inundation, and nutrient availability **(Prihantono *et al.*, 2022)**.

Table 7. Monthly leaf count per mangrove seedling

Plots	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Total	Mean Leaf Count
A1	12.7	18.7	21.5	24	24.1	23.2	17.6	5	141.9	17.73
A2	12.1	17.3	23.5	33.9	26.6	35.5	35.9	27.7	184.7	23.09
A3	19.1	23.1	26.6	35.7	22.8	33.7	39.1	29.4	200.2	25.03
A4	17.2	17.1	17.1	26.9	14.5	29.6	23.7	5.67	151.6	18.94
B1	22.2	25.9	32.4	33.8	17.9	31.5	36	28.9	228.5	28.57
B2	16	19.5	23.2	29.6	15.5	12.7	17.7	18	152.3	19.03

The monthly distribution of natural recruitment (Fig. 7) revealed a pronounced peak in October, particularly for plot B1, which recorded the highest number of naturally recruited individuals. This suggests that the rehabilitated coastal area provided suitable conditions for propagule settlement and seedling establishment during the post-monsoon (October–November in South Sulawesi), consistent with findings from similar mangrove restoration studies where recruitment rates were at their highest during periods of moderate salinity and reduced hydrodynamic stress **(Rahman *et al.*, 2020)**. In this seasonal window, rainfall declines, leading to moderate salinity levels, while calmer seas after the peak monsoon reduce wave and current energy, both of which favor seedling recruitment and establishment.

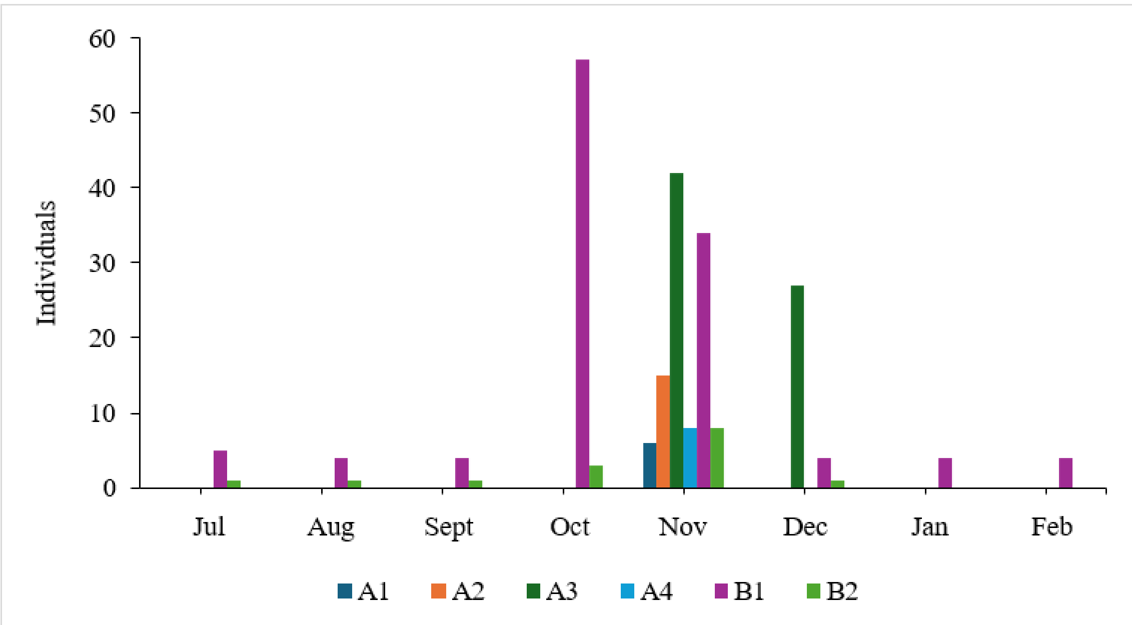

Fig. 7. Natural recruitment of mangrove seedlings per month

The variation in leaf production among plots can be attributed to differences in microhabitat conditions, such as sediment composition, light availability, and hydrological regimes, which directly affect photosynthetic capacity and nutrient assimilation in mangrove seedlings **(Suárez, 2003; Cadiz *et al.*, 2021; Alvarado *et al.*, 2025)**. Notably, plots B1 and A3 demonstrated superior leaf growth, likely reflecting optimal site conditions and possibly higher survival rates, critical indicators of rehabilitation success. The lower leaf counts observed in plots A1 and A4 during later months may indicate stress from seasonal environmental fluctuations or competition among seedlings, highlighting the importance of continuous monitoring to inform adaptive management strategies **(McCord & Pilliod, 2022)**.

In conclusion, the leaf count data and natural recruitment trends collectively indicate that the rehabilitated coastal area in Lantebung supports effective mangrove establishment, with specific plots exhibiting higher growth performance. These findings underscore the importance of site-specific management and the monitoring of seasonal growth dynamics to enhance the long-term success of mangrove restoration initiatives.

CONCLUSION

The assessment of mangrove seedlings' growth performance in the rehabilitated Lantebung coastal area revealed considerable variation in survival and growth among plots. Plot B1 showed the highest survival (83.85%), growth rate (254.97%), and leaf production (28.57 leaves per seedling), indicating that site-specific protective measures and maintenance significantly enhance seedling establishment. *R. apiculata*, the dominant species in B1, demonstrated the best overall performance, suggesting its suitability for future rehabilitation efforts in similar conditions. In contrast plot B2, which is less exposed to strong tidal currents, experienced lower hydrodynamic stress, providing potentially more favorable conditions for species less tolerant to high currents. Plots exposed to strong tidal currents and limited management experienced high mortality. Natural recruitment contributed to maintaining vegetative cover in some plots, highlighting the role of ecological processes in restoration success. These findings emphasize the importance of targeted engineering interventions, continuous monitoring, and adaptive management to optimize long-term survival and growth in mangrove rehabilitation programs, supporting sustainable coastal ecosystem management.

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