

Development of *Rhizophora apiculata* Planting Patterns to Enhance
Survival Rates, Growth rate and Mitigate Coastal Erosion for
Sustainable Mangrove Restoration.

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Abstract

Currently, mangrove forests worldwide are being destroyed and degraded, making restoration essential. Restoration methods include planting *Rhizophora apiculata* (Tall-stilt mangrove) propagates and plant seedlings randomly. This study designed three mangrove planting patterns to evaluate survival and growth rates: 1) Grid, 2) Staggered, and 3) Semicircular, along with a control group (random planting). Each pattern utilized 15 trees with 1-meter spacing within a 15 m² area at the mouth of Sikao river, Sikao District, Trang Province. The results indicated that the Staggered pattern achieved the highest average survival rate at 82.22%, while the Semicircular pattern had the lowest at 40.00%. There were statistically significant differences in survival rates among the planting patterns ($p < 0.05$). However, the growth rates of the surviving mangroves specifically height, stem circumference, and leaf count showed no significant differences ($p > 0.05$). Regarding soil properties, Nitrogen (N), Phosphorus (P), Potassium (K), and organic matter content increased post-planting. Furthermore, the coastal erosion reduction analysis using CFD (Computational Fluid Dynamics) modeling revealed that the Staggered pattern was the most effective in mitigating erosion, as it resulted in a uniform reduction of wave velocity across the study area.

Keywords: Survival rate, Growth rate, Soil properties, Reduce coastal erosion

Introduction

Mangrove forests are among the most vital ecosystems on Earth, serving as essential nurseries for marine life and acting as one of the world's most efficient carbon sinks. They are capable of sequestering over 1,000 tons of carbon per hectare (Donato et al., 2011), which is three times higher than typical tropical forests (Patrick Greenfield, 2024). Furthermore, mangroves act as natural filters for pollutants before they reach the ocean and provide critical coastal protection. By reducing wave energy and water velocity, they facilitate sediment trapping, which stabilizes the shoreline and prevents erosion (Bradley Walters, 2023).

However, between 2000 and 2020, global mangrove areas suffered continuous degradation, with a total loss of 284,000 hectares (K. Federico, 2023). This decline stems from several factors, including canal dredging that alters soil properties and disrupts the natural balance, as well as forest encroachment for fuel wood or port construction. These activities lead to widespread environmental damage, such as declining marine populations, increased

greenhouse gas emissions, and exacerbated coastal erosion due to the loss of complex root systems—like those of *Rhizophora apiculata*—which are essential for binding soil particles.

Thailand's coastline stretches 3,151.13 km, with over 822.81 km currently facing erosion problems, a trend that continues to rise. This issue significantly impacts both the coastal environment and the economy (Department of Marine and Coastal Resources, 2020). Various methods have been employed to prevent erosion, such as constructing concrete walls or breakwaters. However, these structures require substantial budgets and often negatively affect coastal tourism (Sarinya Sanidwong Na Ayutthaya, 2023). In some communities, bamboo fences are used; however, they require vast amounts of bamboo and decay easily, necessitating repairs every 2 to 5 years, which is labor and resource-intensive (Waris Jaroenlerthawin, 2022).

In contrast, mangrove reforestation enhances ecological balance with minimal long-term maintenance. The dense, interlocking root systems effectively reduce water velocity, promote sedimentation, and mitigate erosion while enriching the local ecosystem, ultimately improving the income and quality of life for coastal communities (Mangrove Forest Resources Conservation Office, 2018).

Since planting configurations are a key factor influencing the survival and growth of mangroves, this research aims to study the optimal planting patterns for *Rhizophora apiculata* Blum. The study involves designing three natural planting configurations and one control group to monitor survival and growth rates, as well as analyzing soil properties before and after implementation. Furthermore, Computational Fluid Dynamics (CFD) modeling via FLOW-3D HYDRO will be utilized to simulate wave velocity attenuation for each configuration. By integrating this data with coastal erosion analysis, this research aims to establish sustainable guidelines for mangrove reforestation that maximize survival, growth, and coastal protection efficiency.

Research Questions

1. Does the planting pattern of mangrove affect its survival and growth rates? If so, how?
2. Does the planting pattern of mangrove affect the soil properties in the planting area? If so, how?
3. How do different planting patterns of mangrove contribute to the reduction of coastal erosion?

Hypotheses

1. Different planting patterns of mangrove trees result in variations in survival and growth rates.
2. Soil properties are expected to differ significantly between pre-planting and post-planting periods under various planting patterns of mangrove.
3. Diverse planting patterns of mangrove have different impacts on the mitigation of coastal erosion.

Materials

- | | |
|----------------------|------------------------|
| 1. Mangrove saplings | 2. pH meter |
| 3. Soil NPK Test Kit | 4. Muffle Furnace |
| 5. Planting bag | 6. Measuring Tape |
| 7. SketchUp | 8. CFD (Flow 3D Hydro) |

Methodology

2.1 Site Exploration and Problem Identification

A field survey in Trang Province, conducted in collaboration with the Ban Mod Tanoy Community Enterprise, identified key challenges in mangrove survival, growth, and erosion control. These findings, supported by a literature review and expert consultations, established the framework for this research.

2.2 Study sites

The study area is situated at the mouth of Sikao Canal, Maifad Sub-district, Sikao District, Trang Province, Thailand. The precise experimental site is located at coordinates 7.5377192°N latitude and 99.3142065°E longitude, as illustrated in Figure 1.



Figure 1: The mouth of Sikao Canal, Maifad Sub-district, Sikao District, Trang Province, and the designated study site.

2.3 Design configuration and Mangroves planting preparation

2.3.1 Conceptual Design of Mangrove Planting Configurations

We developed the initial layouts for the mangrove planting configurations using SketchUp software. The designs consist of three distinct patterns: **Pattern 1: Grid**,

Pattern 2: Staggered, and **Pattern 3: Half-circle**. Each experimental plot contains 15 saplings, with a fixed spacing of 1 meter between each plant, covering a total area of 15 square meters per plot. Following the initial design phase, the layouts were presented to subject matter experts for evaluation. Their feedback and recommendations were then integrated to refine and finalize the planting configurations for the field study.

2.3.2 Mangrove Sapling Preparation for Field Planting

We selected mature *Rhizophora apiculata* propagules from their natural habitat, ensuring a length of approximately 20–25 cm. These propagules were soaked in saltwater with a salinity of 20 ppt for two weeks to acclimate them to the coastal environment and prevent dehydration or nutrient deficiency. Following the acclimation period, the propagules were planted in nursery bags and placed along a brackish water canal within the intertidal zone for three months. Finally, we selected healthy saplings with a height of approximately 30 cm and at least two pairs of true leaves for transplanting into the study site.

2.4 Soil Data Collection

Soil properties were measured following the GLOBE Program protocols, focusing on pH levels, macronutrients (N, P, K), organic matter, and soil texture

1. Soil sampling was conducted across four designated experimental areas: 1) the Grid planting pattern, 2) the Staggered planting pattern, 3) the Half-circle planting pattern, and 4) the Random planting pattern, which served as the control group.

2. Soil samples were collected from within each planting configuration both before and after the *Rhizophora apiculata* planting period. Samples were extracted from the soil surface down to a depth of 15 cm. At each site, the soil was thoroughly mixed before a 600 g sub-sample was randomly selected—totaling 12 samples in all—and bagged separately for laboratory analysis of various indices. To study soil properties, the samples were air-dried and oven-dried to remove moisture. The dried soil was then mixed with distilled water to measure the pH level using a pH meter, while nutrient levels were determined using a professional soil NPK test kit. The remaining soil was used for organic matter analysis by weighing the samples before and after heating them in a furnace at 450°C for 5 hours; the organic matter content was then calculated based on the weight loss. Finally, the texture and color of the soil were observed and compared against standard classification charts.

2.5 Mangrove Planting in the Study Area

The field implementation was conducted at the mouth of the Sikao Canal, Maifad Sub-district, Sikao District, Trang Province, to plant *Rhizophora apiculata* using the four designed configurations.

1. The study site was divided into experimental plots for the four different planting patterns. Each plot measured 3 meters in width and 5 meters in length, with a 10-meter buffer zone between plots. The experiment was conducted with three replicates for each planting pattern, totaling 12 experimental plots, as illustrated in Figure 2.

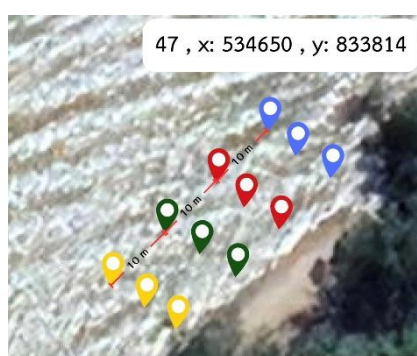


Figure 2: The 12 experimental plots located at the mouth of Sikao Canal, Sikao District, Trang Province.

2. We conducted the field planting by precisely marking the position of each mangrove sapling within the designated plots. Planting holes were excavated to a depth of approximately 15 cm, and the saplings were planted according to their respective designs. Immediately after planting, the initial height and stem circumference of each sapling were measured and recorded as baseline data. The survival and growth rates were then monitored and recorded monthly from October 2025 to January 2026. Finally, the collected data were compiled for further statistical analysis.

2.6 Sediment Accretion Study

To monitor sediment accretion, we installed 1.5-meter bamboo stakes at three specific points within each experimental plot (one point per row). The initial sediment level was marked on each stake as a baseline. Subsequently, the increase in sediment height was measured at every point across all plots on a monthly basis throughout the duration of the study.

2.7 Study of Wave Velocity Reduction for Coastal Erosion Mitigation

The study analyzed wave velocity before and after passing through the four mangrove planting configurations. A 5-year growth scenario was simulated using Computational Fluid Dynamics (CFD) software, specifically FLOW-3D HYDRO, as follows:

1. Mangrove structures were modeled as cylindrical shapes, referencing the research of Eldina Fatimah. Each tree was designed with a trunk diameter of 3 cm and stilt roots with a diameter of 0.5 cm, based on the study by Wicharn Inthasothi (2010). The 3D models were developed using SketchUp software.

2. The generated models were imported into FLOW-3D HYDRO for testing. The simulation was configured with regular waves at a velocity of 6 m/s to replicate typical coastal wave conditions. The Data Visualization (wave velocity profiles) for each planting pattern was then closely observed.

3. The Data Visualization results were analyzed to compare the wave velocity reduction after passing through each mangrove configuration. This data was used to discuss and evaluate the efficiency of each pattern in mitigating sustainable coastal erosion.

2.8 Data Analysis

1. Survival Rate Analysis: The survival rate for each planting configuration was determined by calculating the arithmetic mean and standard deviation (S.D.). The survival percentage for each mangrove planting pattern was calculated using the following equation:

$$\text{Survival rate (\%)} = \frac{\text{Number of plants that survived}}{\text{All number of plants}} \times 100$$

2. Comparative Statistics: A One-way Analysis of Variance (One-way ANOVA) was employed to compare the survival rates across all four planting configurations. All statistical tests were conducted at a significance level of $\alpha = .05$ to determine meaningful differences between the groups.

3. Growth Rate Analysis: The growth rates of the mangroves were analyzed using the arithmetic mean and standard deviation (S.D.). To determine the impact of different planting patterns, a One-way Analysis of Variance (One-way ANOVA) was used to compare the growth performance across all configurations, with statistical significance tested at $\alpha = .05$.

4. Soil Property Analysis: Soil properties—including pH, organic matter, macronutrients (NPK), and soil texture—were analyzed for all 12 experimental plots both before and after the planting period. The data for each planting configuration were processed using the arithmetic mean and standard deviation (S.D.) to identify changes in soil quality.

5. Sediment Accretion Analysis: The sediment accretion data were analyzed using the arithmetic mean and standard deviation (S.D.). A One-way Analysis of Variance (One-way ANOVA) was employed to compare the sediment accumulation rates among the different planting configurations, with statistical significance determined at $\alpha = .05$.

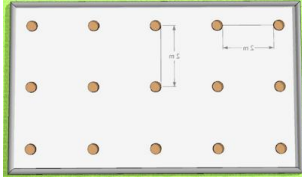
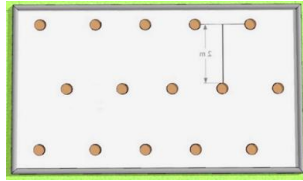
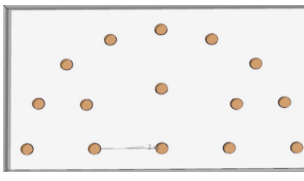
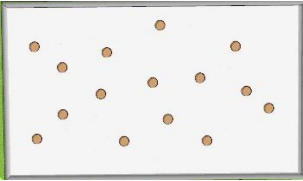




Results

Part 1: The Development of *Rhizophora apiculata* Blum Planting Patterns to Enhance Survival and Growth Rates

1.1 Development of Planting Configurations to Enhance Mangrove Survival Rates

The developed *Rhizophora apiculata* Blum planting configurations consist of three specific patterns and one control group: 1) Grid pattern, 2) Staggered pattern, 3) Half-circle pattern, and 4) Random pattern (Control). The visual representations of each configuration are presented in Table 1.

Table 1: Schematic designs and field implementation of the different mangrove planting configurations.

Pattern: 1 Grid	Pattern: 2 Staggered	Pattern: 3 Half-circle	Control: Random
			
			

The *Rhizophora apiculata* Blum saplings were planted with 15 trees per plot, spaced 1 meter apart. The experiment was conducted with three replicates per configuration over a 3-month period, from October 2025 to January 2026. The results are presented in Table 2.

Table 2: Average survival rates of mangroves across different planting configurations.

Planting pattern	Mean Survival (Trees)
Grid	10.33 ± 1.53 ^a
Staggered	12.33 ± 1.53 ^b
Half-circle	6.00 ± 1.00 ^c
Control	8.00 ± 1.00 ^d

Note: Different letters in the same column indicate statistically significant differences (p= 0.05).

The results indicated that mangroves planted in the staggered pattern achieved the highest average survival rate of 12.33 ± 1.53 trees, while the half-circle pattern had the lowest at 10.33 ± 1.53 trees. One-way ANOVA at a significance level of .05 confirmed that survival rates among the different configurations were statistically significant. In terms of percentages, the Staggered pattern showed the highest survival at 82.22%, followed by the row pattern (68.89%), the random pattern (control) (53.33%), and the Half-circle pattern, which had the lowest survival at 40.00%. These results are illustrated in Figure 3.

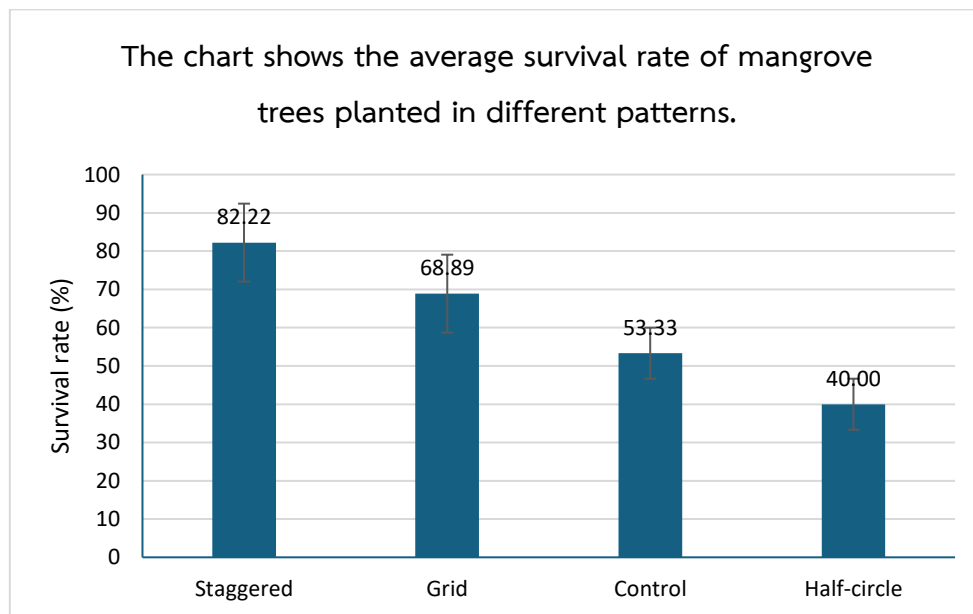


Table 3: Cost-effectiveness analysis of different *Rhizophora apiculata* Blum planting configurations.

The cost-effectiveness analysis of each planting configuration in relation to survival rates is presented in Table 3.

Table 3: Cost-effectiveness analysis of different *Rhizophora apiculata* Blum planting configurations.

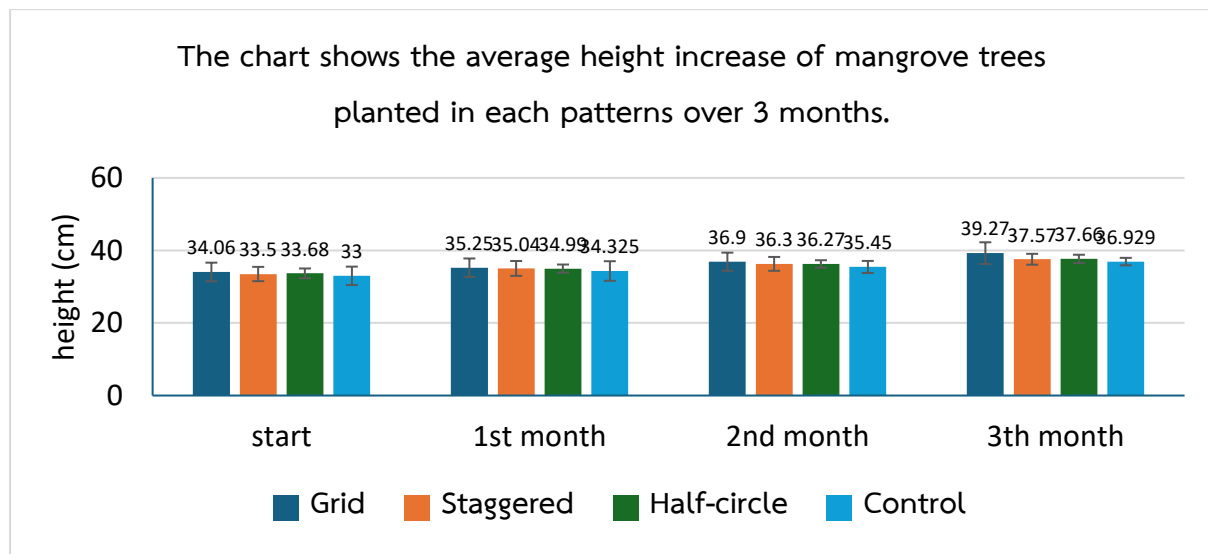
Planting pattern	Investment Cost (THB)	Time (hr)	Survival rate (%)	Cost-Effectiveness
Grid	225	0.75	68.89	40.22
Staggered	225	0.75	82.22	48.72
Half-circle	225	1.00	40.00	17.78
Control	225	0.60	53.33	39.50

The cost-effectiveness analysis reveals that the staggered pattern achieved the highest score of 48.72, making it the most viable and efficient configuration for mangrove plantation.

1.2 Development of Planting Configurations to Enhance Mangrove Growth Performance.

The results of the 3-month study on the growth performance of mangroves across the four planting configurations are as follows:

1.2.1 Growth Performance in Terms of Plant Height Across Different Configurations. (Figure 4)



The study found that the row pattern achieved the highest average height increment, followed by the staggered and half-circle patterns, respectively. However, these differences were not statistically significant at the .05 level.

1.2.2 Growth Performance: Stem Circumference Increment Across Different Configurations.

(Figure 5)

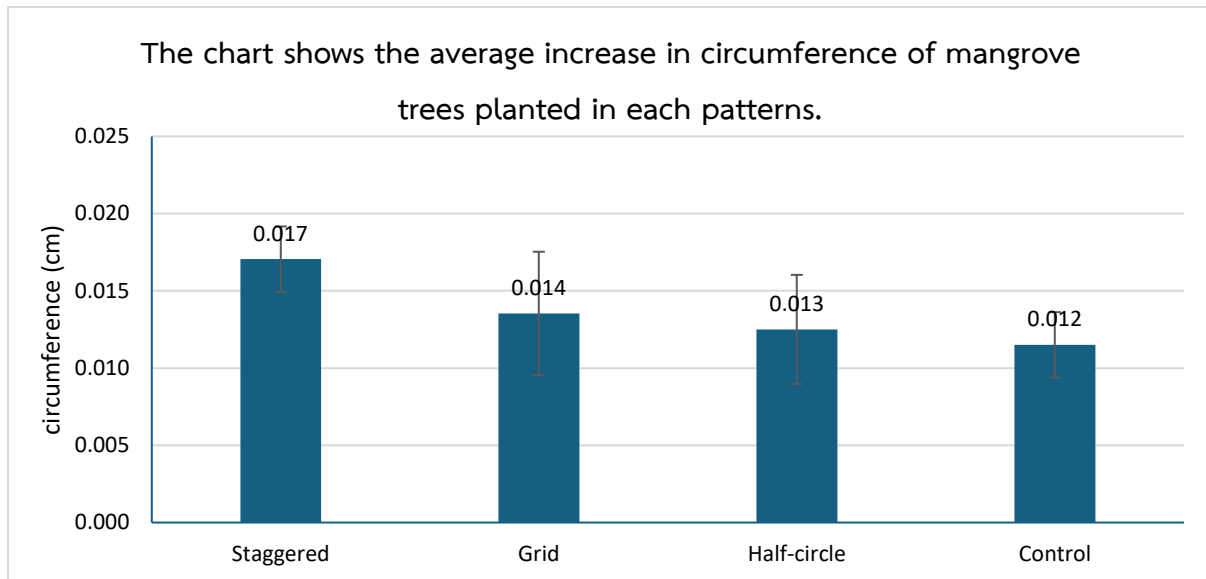


Figure 5: Average stem circumference increment of *Rhizophora apiculata* Blum across different planting configurations.

The study indicates that the staggered pattern exhibited the highest average stem circumference increment, followed by the row and half-circle patterns, respectively. However, these findings showed no statistically significant differences at the .05 level.

1.2.3 Growth Performance: Leaf Count Increment Across Different Configurations.

(Figure 6)

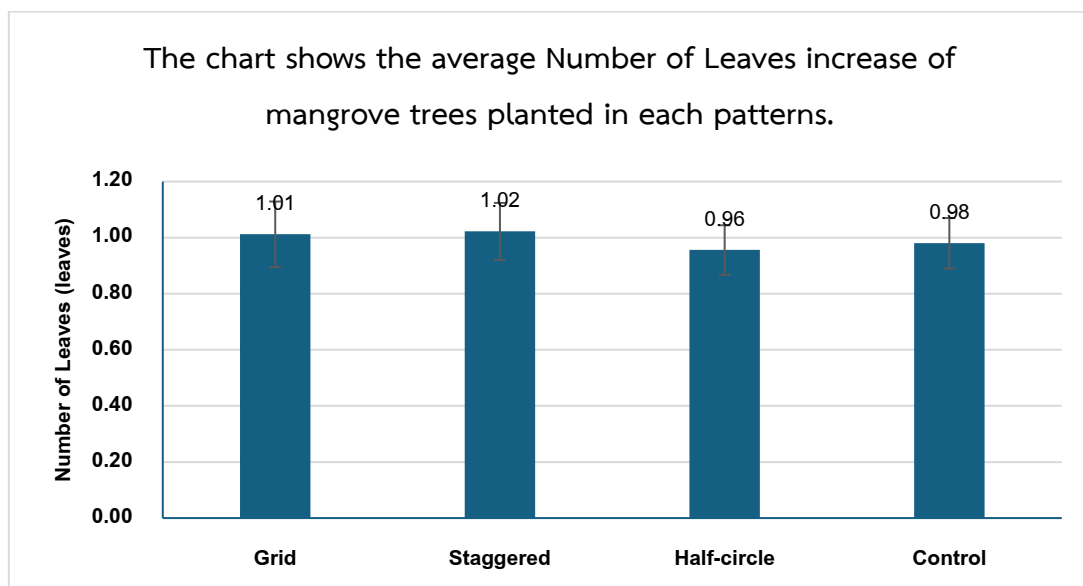


Figure 6: Average leaf count increment of *Rhizophora apiculata* Blum across different planting configurations.

The study found that the half-circle pattern exhibited the highest average leaf count increment, followed by the row and staggered patterns, respectively. However, these differences were not statistically significant at the .05 level.

Part 2: Study of Soil Sedimentation and Soil Properties Before and After Planting Mangroves Across Different Configurations.

2.1 Results of Soil Sedimentation and Soil Properties Analysis: A Comparative Study Before and After Implementation Across Different Configurations.

The results of soil sedimentation rates across different planting configurations over a 3-month period are illustrated in Figure 7.

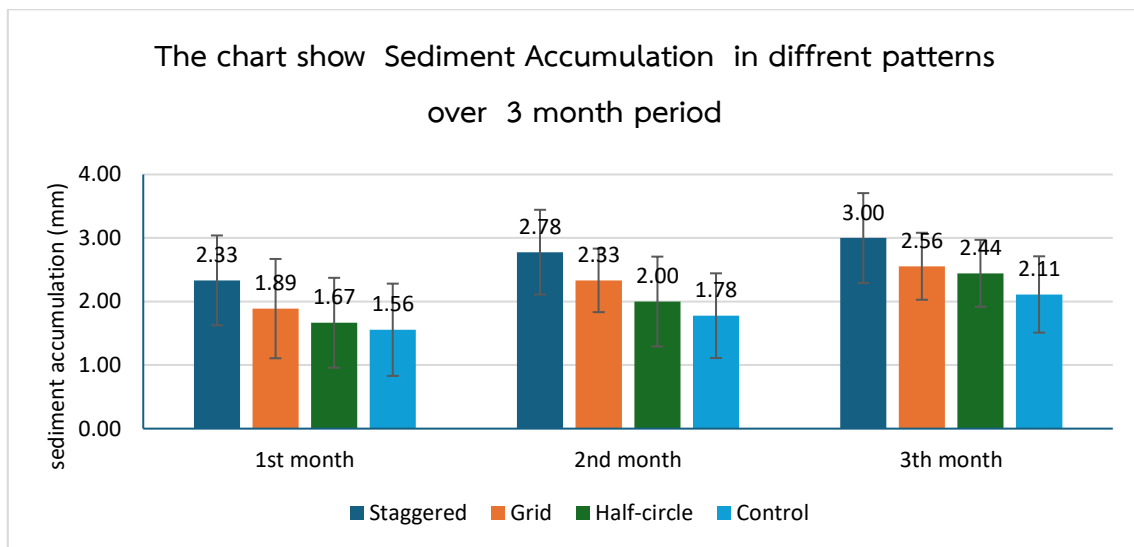


Figure 7: Comparison of soil sedimentation levels across different planting configurations over a 3-month period.

The findings indicate that the staggered planting configuration achieved the highest average sediment accretion. However, statistical analysis at the .05 level revealed no significant differences in sedimentation levels among the various configurations during the 3-month study period.

2.2 Analysis of Soil Properties Before and After Planting *Rhizophora apiculata* Blum Across Different Configurations

The study evaluated soil properties across different planting configurations using a triple-replicate design (3 replicates). Key parameters including soil pH, Organic Matter (OM), primary macronutrients (N, P, K), and soil texture were measured to assess changes in soil quality. The comparative results are presented in Table 4 and Table 5.

Table 4: Soil properties (pH, Organic Matter, and Texture) before and after planting *Rhizophora apiculata* Blum across different configurations.

Planting pattern	Soil texture	pH		Organic matter	
		before	after	before	after
Grid	Sandy loam	6.21 ± 0.42 ^a	6.17 ± 0.26 ^a	1.87 ± 0.03 ^a	2.26 ± 0.02 ^b
Staggered	Sandy loam	6.43 ± 0.38 ^a	6.42 ± 0.20 ^a	1.84 ± 0.02 ^a	2.66 ± 0.02 ^c
Half-circle	Sandy loam	6.26 ± 0.41 ^a	6.25 ± 0.42 ^a	1.86 ± 0.03 ^a	2.14 ± 0.03 ^d
Control	Sandy loam	6.24 ± 0.41 ^a	6.24 ± 0.20 ^a	1.84 ± 0.20 ^a	2.21 ± 0.02 ^e

Note: Different letters in the same column indicate statistically significant differences ($p \leq 0.05$).

The study revealed that the soil texture across all planting configurations was characterized as sandy loam. While soil pH showed no significant change before and after planting, the organic matter content increased across all patterns. Specifically, the staggered configuration exhibited the highest organic matter content. This correlates with the findings that the staggered pattern also achieved the highest survival rate and sediment accretion.

Table 5: Comparison of soil nutrient levels (N, P, K) before and after planting *Rhizophora apiculata* Blum across different configurations.

Planting pattern	N		P		K	
	Before	After	Before	After	Before	After
Grid	Trace	Trace	Trace	Trace	Trace	Trace
Staggered	Trace	Low	Trace	Low	Trace	Trace
Half-circle	Trace	Trace	Trace	Trace	Trace	Trace
Control	Trace	Trace	Trace	Trace	Trace	Trace

Soil fertility analysis at the planting sites revealed that initial levels of Nitrogen (N), Phosphorus (P), and Potassium (K) were only present in trace amounts. However, post-planting assessments showed a significant increase in N and P concentrations across all configurations.

Part 3 : Study of Wave Velocity Using Computational Fluid Dynamics (CFD) Models.

The results of the wave velocity study using CFD simulations are presented in Figure 8.

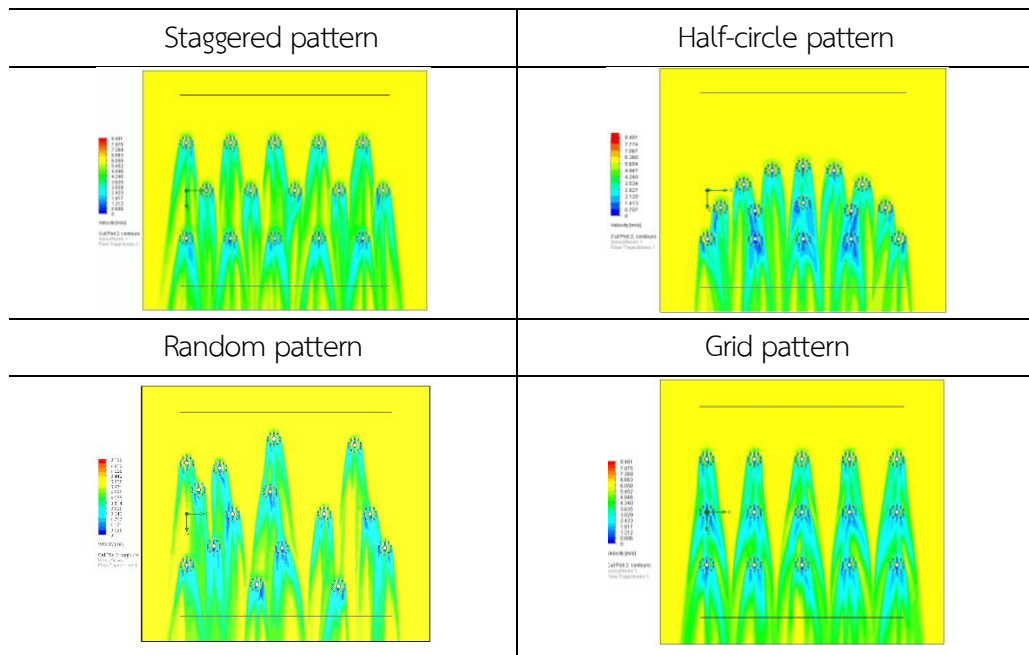


Figure 8: CFD models illustrating wave velocity as it passes through various mangrove planting patterns.

The study found that different planting patterns possess varying capabilities in reducing wave velocity. In the simulations, the light green and blue zones behind the mangrove clusters indicate areas where wave velocity has significantly decreased. The staggered pattern demonstrated a continuous and more comprehensive reduction in wave velocity across the study area compared to other patterns. This is because the mangroves in the second row effectively block the gaps left by the first row, forcing the water to change direction and continuously impact the trunks. Consequently, this pattern creates the most extensive area of reduced wave energy behind the mangrove barrier.

Conclusion and Discussion

The development of planting patterns for *Rhizophora apiculata* Blum to enhance survival rates, growth rates, and sustainable coastal erosion reduction has led to the following conclusions:

The study of survival rates across different planting patterns revealed that the staggered pattern achieved the highest average survival rate at 82.22%, while the semicircular pattern yielded the lowest at 40.00%. Statistical analysis at a significance level of .05 indicated significant differences among the patterns. The high survival rate in the staggered pattern is attributed to its complex arrangement and uniform distribution, which effectively

dissipates wave energy. This aligns with research by Horstman et al., which notes that the complex root and stem systems of mangroves reduce wind and water velocity, promoting sediment accretion and reducing basal erosion. Conversely, the linear (row) pattern exhibited lower survival rates due to the formation of "channels" or gaps. This is consistent with Vandenbruwaene et al., who found that organized linear arrangements compress water flow through gaps, resulting in velocities and shear stresses higher than the average, leading to localized erosion. The semicircular pattern performed poorly because the outer perimeter bears the brunt of wave impact and concentrated energy. According to Tinoco and Coco, this geometry increases wave velocity at the arc's edges, creating high shear stress that erodes soil around the roots.

Regarding growth, the linear pattern showed the highest average increase in height, whereas the semicircular pattern showed the least. The height advantage in linear planting is likely due to the shielding effect, where subsequent rows experience reduced wave impact. However, the staggered pattern recorded the highest increase in stem circumference. This suggests that since all trees in a staggered layout are uniformly exposed to wave forces, they adapt by increasing structural girth for stability and survival. Notably, statistical analysis showed no significant difference in growth rates among the patterns at the .05 level.

Post-planting soil analysis characterized the texture as sandy loam. While pH levels showed no significant change, soil organic matter (SOM) and macronutrients (N, P, K) increased across all patterns. The staggered pattern exhibited the highest sediment accretion at 2.10 mm, directly correlating with the highest organic matter content. These findings support research by Dharmayasa et al., confirming that mangroves enhance soil nutrient profiles and organic matter.

The study found that mangrove planting significantly reduces wave velocity as roots obstruct flow and induce turbulence, consistent with Lekshmy Devi's findings. Computational Fluid Dynamics (CFD) simulations predicting a 5-year maturity stage showed that the staggered pattern is the most effective at sustainable coastal erosion reduction. Its uniform and comprehensive coverage leads to consistent wave attenuation and maximum sediment deposition. According to Zhang et al., staggered arrangements can reduce wave energy by 20–30% more than linear ones due to higher drag coefficients. In the semicircular pattern, velocity reduction was concentrated in the center, while high-velocity flow at the edges caused peripheral erosion. The control group (random planting) showed inconsistent attenuation, leading to fluctuating sedimentation zones. Finally, the linear pattern was the

least effective for erosion control as the gaps between rows accelerated wave velocity and induced channel erosion, as corroborated by Vandenbruwaene et al.

The developed planting patterns for *Rhizophora apiculata* Blum significantly affect survival rates ($p < .05$), with the staggered pattern being the most effective. While growth rates did not differ significantly across patterns, mangrove integration improved soil organic matter and nutrient levels (N, P, K). CFD modeling confirms that the staggered pattern provides the most efficient and sustainable protection against coastal erosion.

Acknowledgements

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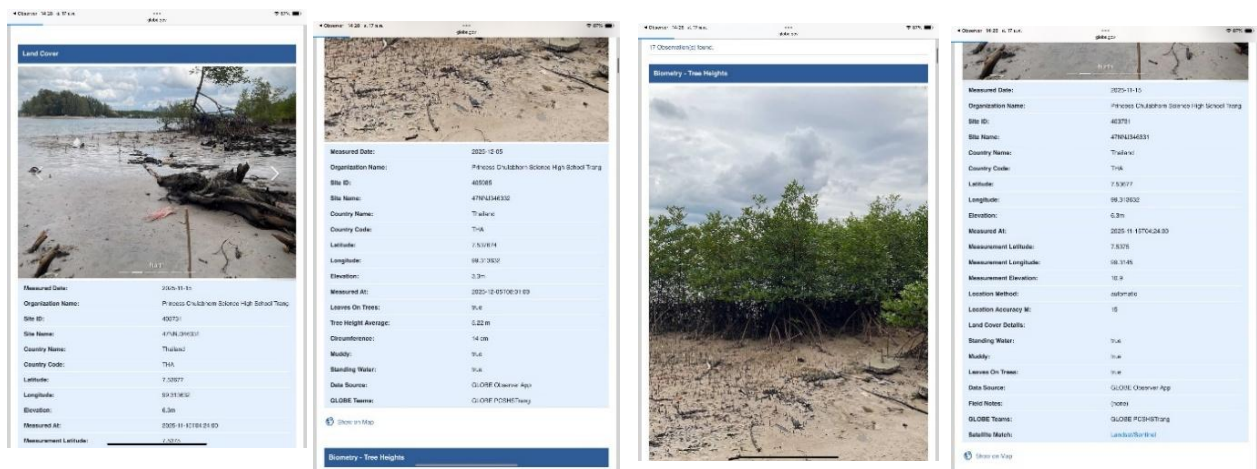
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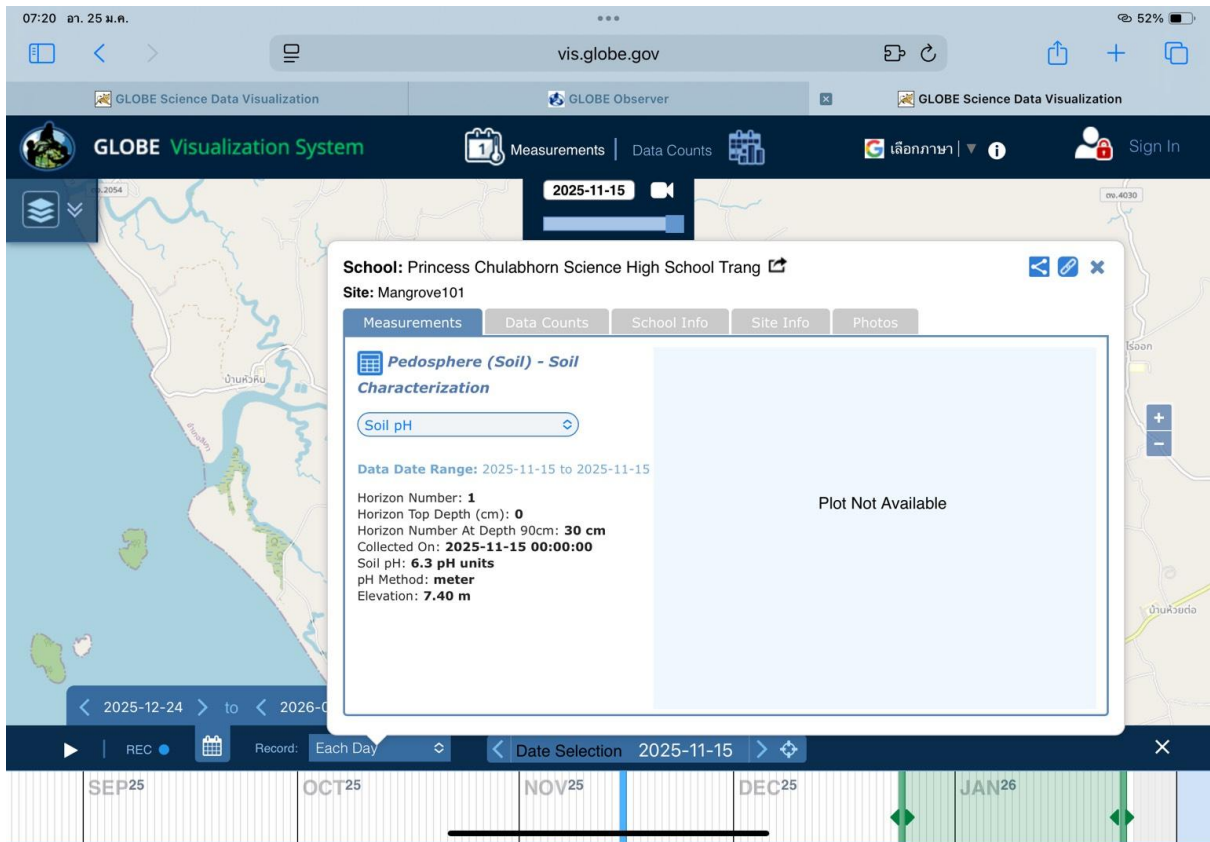
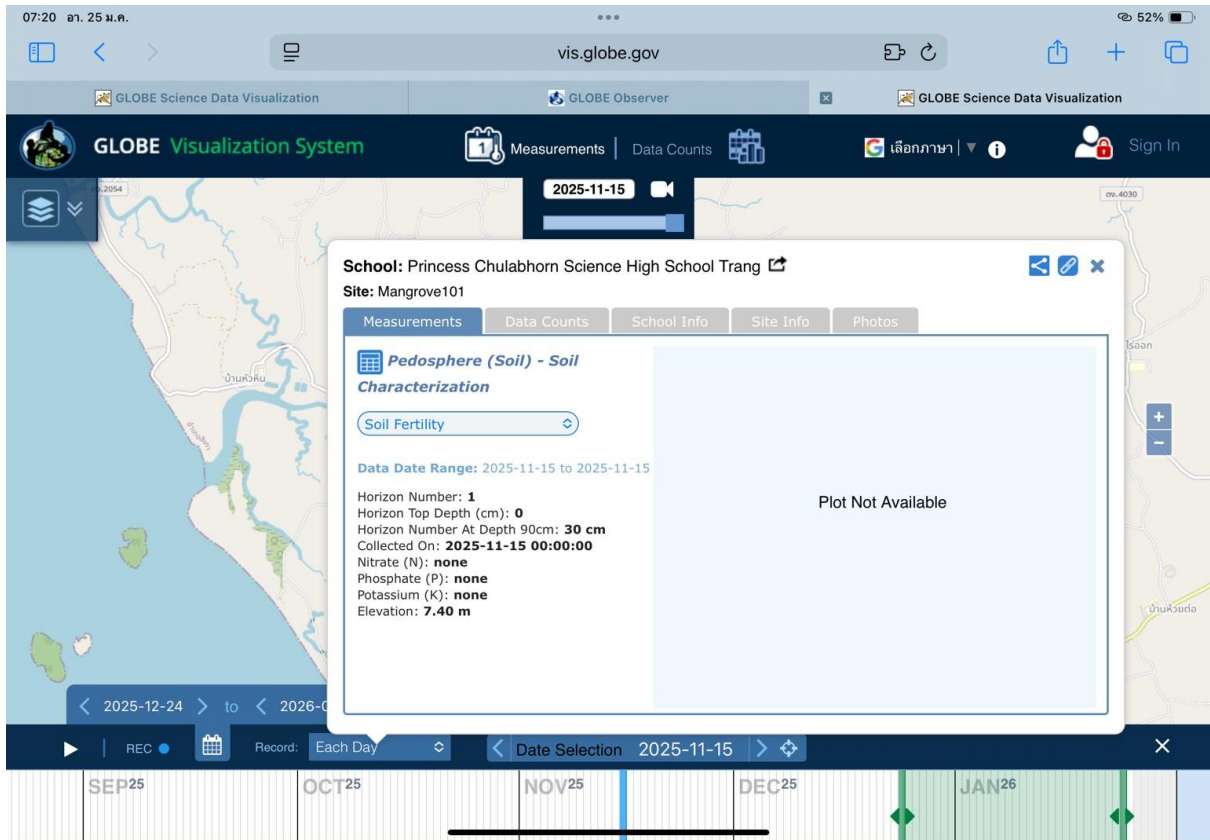
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GLOBE's databases





Badges

I AM A COLLABORATOR

This research was conducted through a multi-sectoral collaboration. The researchers partnered with the Baan Mod Tanoy Community Enterprise in Kantang District, Trang Province, to survey issues regarding mangrove forest degradation and co-develop effective solutions. Furthermore, the team collaborated with Rajamangala University of Technology Srivichai (Trang Campus) to establish experimental frameworks and engage in scientific discussions and debates over the results. Throughout the process, the research team operated systematically with clear task delegation and employed a rational, evidence-based approach to collaborative problem-solving.

I MAKE AN IMPACT

Our study aims to solve community problems sustainably by starting with local observations and working closely with the community. We have developed a systematic plan to tackle coastal erosion caused by the loss of coastal forests. Using environmentally friendly approaches, we strive to improve the quality of life for local people, revitalize marine biodiversity, and address the global warming crisis in a sustainable way.

I AM PROBLEM SOLVER

The research on developing planting patterns for small-leaf mangroves reflects the application of Earth System Science to achieve sustainable environmental solutions. By investigating the interactions between soil, vegetation, and wave dynamics through field experiments and Computational Fluid Dynamics (CFD) simulations, the team identified that a "staggered" pattern most effectively enhances seedling survival and reduces coastal erosion. These findings not only restore vital mangrove ecosystems but also uplift the well-being of coastal communities. This dedication to evolving from being problem-studiers into innovators of real-world solutions embodies the spirit of GLOBE researchers, who utilize Earth System Science to foster a better world.