Mangrove Restoration Using Rubberwood Fly Ash to Produce Biodegradable Seedling Pots for Coastal Erosion Control

Siriphat Sirikunpitak,[a] Kuaanan Techato,[a] Payom Rattanamanee,[b] Apichat Choomkong,[c] and Khamphe Phoungthong [a,*]

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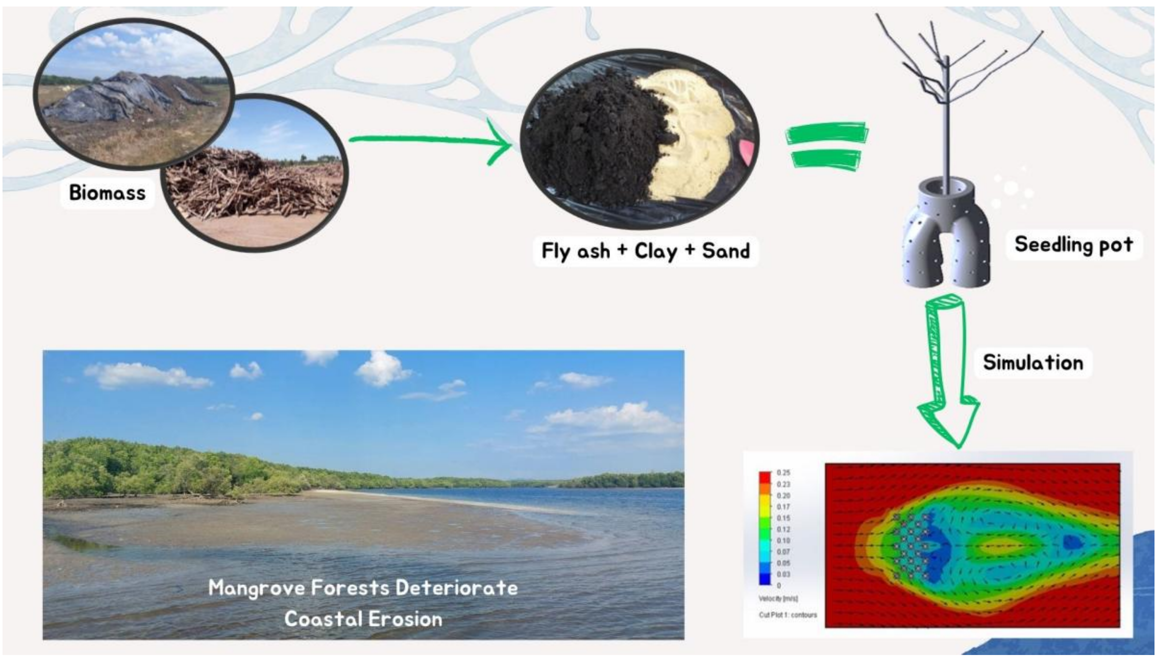
GRAPHICAL ABSTRACT



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The increasing amount of fly ash from daily energy combustion, coupled with land use changes from mangrove forests, has led to an increase in severe coastal erosion. This study aims to utilize fly ash by adding value to biodegradable nursery pots, which can manage fly ash and reduce the use of seedling bags. The pots also have indirect benefits in preventing coastal erosion. The seedling pots are made from rubberwood fly ash (RWFA), clay, and sand. The composition of RWFA is analyzed using X-ray diffraction and fluorescence spectroscopy. The total concentration of a specific contaminant in a waste or soil sample is measured using the total threshold limit concentration (TTLC). Hydrodynamic simulations are conducted to optimize the layout of the pots to reduce the wave velocity. This study determined that RWFA, which is composed of 38.9% CaO, 11.3% SiO_2, 8.9% organic matter, 8.8% total K_2O, 1.0% total P_2O_5, and 0.006% total N, can be used as an ingredient in pots and plant nutrients. Moreover, the seedling pot design can reduce the speed of the water velocity by placing it in a suitable position. Furthermore, the TTLC value of the pot does not exceed the standard value.

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Keywords: Biodegradable pots; Rubberwood fly ash; Attenuation wave energy; Computational fluid dynamics; Restoration mangrove forest

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INTRODUCTION

Climate change is inducing an increase in the intensity of weather events and the ocean environment, leading to rapid coastal erosion and shoreline changes. Coastal erosion is a global environmental problem, including in Thailand (Nidhinarangkoon *et al.* 2023; Department of Marine and Coastal Resources 2024). This problem is caused by various factors, both natural and human-induced, such as deforestation, land management, road construction, urbanization, agriculture, and industry (Gantulga *et al.* 2023), affecting coastal ecosystems, coastal communities, and economic resources (Office of Natural Resources and Environmental Policy and Planning 2020; Dong *et al.* 2024).

Globally, coal-fired power generation produces over 500 million tons of fly ash annually (Mathapati *et al.* 2022). Bhatt *et al.* (2019) reported that there is significant potential for the utilization of fly ash, as evidenced by the fact that China, India, and the United States had fly ash utilization rates of 45%, 38%, and 65%, respectively. Currently, biomass power plants produce fly ash in every region in Thailand, which is in line with the country's Power Development Plan (PDP2018 Revision 1) target of having a total power generation capacity of 73,266 MW by 2050 (Energy Policy and Planning Office 2020). Rubberwood biomass, derived from the large number of rubber plantations in Southern Thailand, can be used for various purposes, such as generating energy through combustion, gasification, or conversion it into biofuels (Department of Alternative Energy Development and Energy Conservation 2021; Kongto *et al.* 2021). One of the major challenges facing biomass power plants, particularly those using rubberwood as fuel in Southern Thailand, is the amount of fly ash generated during combustion, which poses significant environmental and operational issues (Wongsapai *et al.* 2020; Zhou *et al.* 2022). RWFA is mainly composed of calcium oxide, potassium oxide, magnesium oxide, silicon dioxide, and aluminum oxide. Previous research showed that fly ash is useful (Nayak *et al.* 2022). For example, fly ash can be used to improve water quality, soil quality, and agricultural wastewater treatment systems and as a component in cement production, road construction, and brick manufacturing (Suwunwong *et al.* 2021, Hashem *et al.* 2023)

Mangroves are essential (Brunier *et al.* 2019) because they act as natural seawalls (Amma and Bhaskaran 2020) and reduce the height and intensity of waves as they approach the shore (Rasmeemasmuang and Sasaki 2015). Mangroves are ecosystems that provide habitat for aquatic animals. Coastal areas with intact mangrove ecosystems suffer less damage than areas where mangroves were cleared (Senger *et al.* 2021; Thieu *et al.* 2024), highlighting the important role of mangroves in protecting and building coastal resilience. Conservation and restoration of mangrove ecosystems can help mitigate the impacts of natural disasters and provide other valuable ecosystem services (Sunkur *et al.* 2023). Currently, many agencies and organizations, both governmental and private, have partnered with communities in mangrove restoration efforts, particularly in joint mangrove planting initiatives (Gorman *et al.* 2022). However, some inherent weaknesses contribute to the low survival rate of planted mangroves. Mangrove survival at all growth stages is threatened by difficulties with seed recruitment, and environmental conditions, such as soil type and soil conditions (Fickert 2020). For this reason, mangrove is propagated using pods in nursery bags. The mangrove pods take approximately 2 weeks to grow roots, and when the roots are in the soil, it takes approximately 2 weeks to sprout. Generally, the seedlings ready for transplanting should be at least 30 to 50 cm tall and have at least four to six leaves. Usually, it takes at least 3 months to cultivate the seedlings before being moved to the area that needs to be restored (Vernon 2010). During the process of moving mangrove seedlings from the nursery bags to the planting area, problems, such as damaged mangrove roots, cause the mangroves to be unable to grow or find food when they are planted in the planting area, resulting in the survival rate of the mangroves not achieving the target.

This study focuses on the management of fly ash to eliminate it by adding value to biodegradable nursery pots, which can manage fly ash and reduce the use of seedling bags. In addition, the shape of the created pots is designed to be consistent with the characteristics of mangrove roots. Because the pots that were created have four hollow legs, when the mangrove trees grow, the roots can penetrate the soil in the area. The designed pots will be simulated using a mathematical model to simulate the case of placing the pots in a real area, which will affect the change in water velocity.

The results of the model, which show the velocity and direction of water changes when waves collide with the nursery pots, provide an understanding of the dynamics and help predict the changes and facilitate management in the field, which will be useful both in experiments and calculations when applied effectively. The material design of the pot should prioritize saltwater resistance, sunlight tolerance, and suitability for mangrove forest flow routing. The shape and size of the pot should promote root system growth and should be designed appropriately for the *Rhizophora apiculata* species. Seedlings can be planted in small pots with sufficient drainage holes to prevent waterlogging, and the pot should have holes for adding more soil as the tree grows.

METHODOLOGY

Analyzing the fly ash and soil samples helps in determining the composition, grain size, and density, particularly in soil samples. These factors influence how easily the soil erodes when exposed to water currents and wave action.

Raw Materials

Rubberwood fly ash

In this study, rubberwood fly ash (RWFA) was collected from biomass power plants in the southern part of Thailand. The chemical properties were determined *via* standard procedures using an X-ray fluorescence (XRF) spectrometer (Zetium, PANalytical, Netherlands) and an X-ray diffractometer (XRD) (Empyrean, PANalytical, Netherlands). The results were analyzed at the Office of Scientific Instrument and Testing (OSIT), Prince of Songkla University, Thailand. The plant nutrient analysis using Inductively Coupled Plasma - Atomic Emission Spectrometry (ICP-AES METHOD ANALYSIS) were analyzed at the Central Instrumentation Unit, Faculty of Science, Prince of Songkla University.

Sand and clay

In this study, sand and clay were collected from the Kantang Silviculture Research Station. The grain size was determined using the ASTM D422 (2007) standard test method of particle size analysis of soils with sieving test and hydrometer test from Kasetsart University, Thailand.

Preparation of Seedling Pots

To investigate the feasibility of creating mangrove pots using various ratios of RWFA, sand, and clay (*i.e.*, 3:1:1, 2:2:1, and 1:3:1), the following procedures were conducted using the hand-forming process and heat treatment:

1) Dry mixing: Combined the dry ingredients (RWFA, sand, and clay) in the desired proportions after sifting and weighing. Mixed thoroughly to ensure even distribution.

2) Wet mixing: Water (10% of total dry weight) was added gradually to the dry mixture while mixing until a homogeneous, moist, and moldable consistency is achieved.

3) Mold filling: The mixed material was transferred into molds and pressed firmly to eliminate air pockets.

4) Drying and curing: The pots were air-dried for a week, then cured in an oven at a high temperature (800 °C) for 12 h to strengthen the structure. The objective was to test the durability of these innovative mangrove seedling containers in the mangrove environment by mimicking the shape of the mangrove roots.

Simulation of Free Surface Studies: SolidWorks "Intersect" Feature

This study aims to explore the beneficial application of mangrove planting pots for energy attenuation, direction, and wave velocities. In the modeling process, the free surface studies principle was used to simulate the mangrove seedling pots, as shown in Fig. 1.

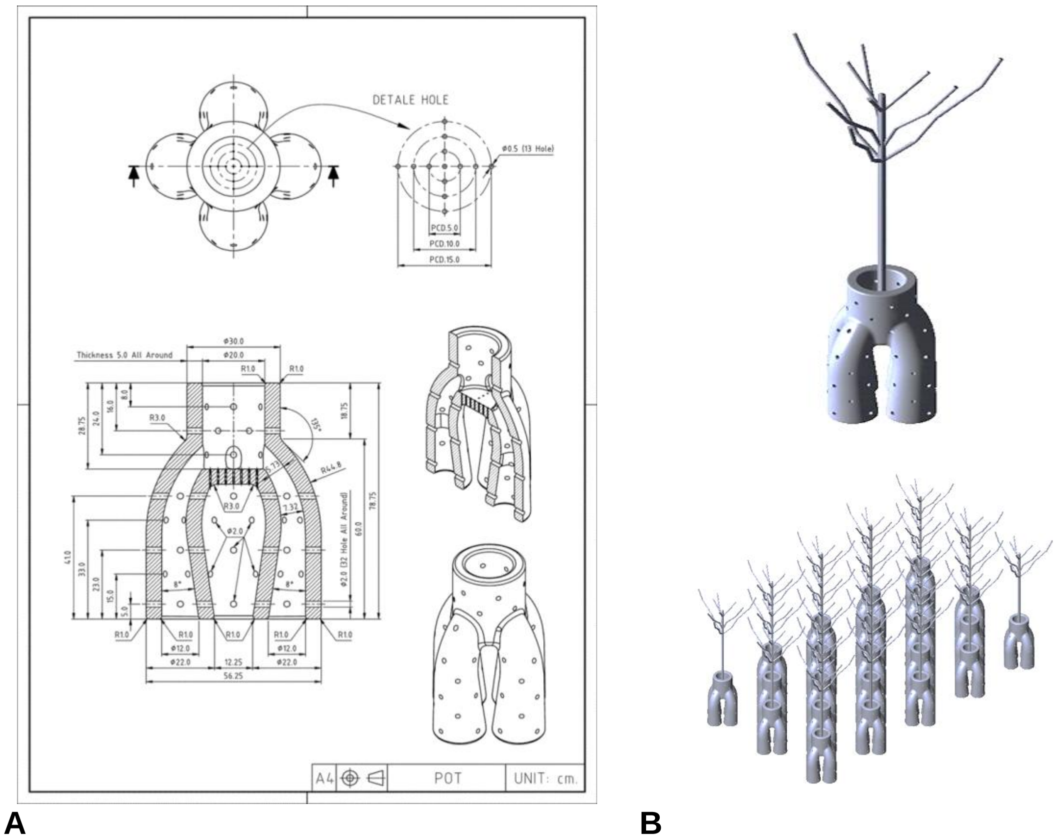


Fig. 1. Seedling pots: a) Schematic dimensions, b) Solid body, and positioning and spacing of pots

This study involves two experimental cases designed to compare the effectiveness of pot placement efficiency. The cases were divided into two to compare the efficiency of pots with four hollow legs, focusing on how different placement patterns influence water movement.

Case 1: The pots were placed at a straight angle, simulating water movement with three strokes. In stroke 1, water flows toward the first leg; in stroke 2, water collides with the second and third legs simultaneously; and in stroke 3, water hits the fourth leg.

Case 2: The pots were placed at an acute angle by rotating the pots from Case 1 by 45°c, simulating water movement with two strokes, where the water hits both front legs in stroke 1 and the water hits both rear legs in stroke 2. This setup ensures a balanced distribution of water throughout the pot.

The results of these experimental cases are expected to provide insights into the optimal pot placement to observe changes in water velocity.

Scenario 1 (Flowing water) was conducted in a still water area under the following experimental conditions determined based on the height of the four hollow legs and the height of the pot neck, as shown in Fig. 1:

1. Water depth = 0.25 m, water velocity = 0.25 m/s;

2. Water depth = 0.50 m, water velocity = 0.50 m/s;
3. Water depth = 0.70 m, water velocity = 1.00 m/s.

Under each condition, 23 intertidal pots were arranged in a zigzag with 0.5 m spacing between pots, as illustrated in Fig. 2.

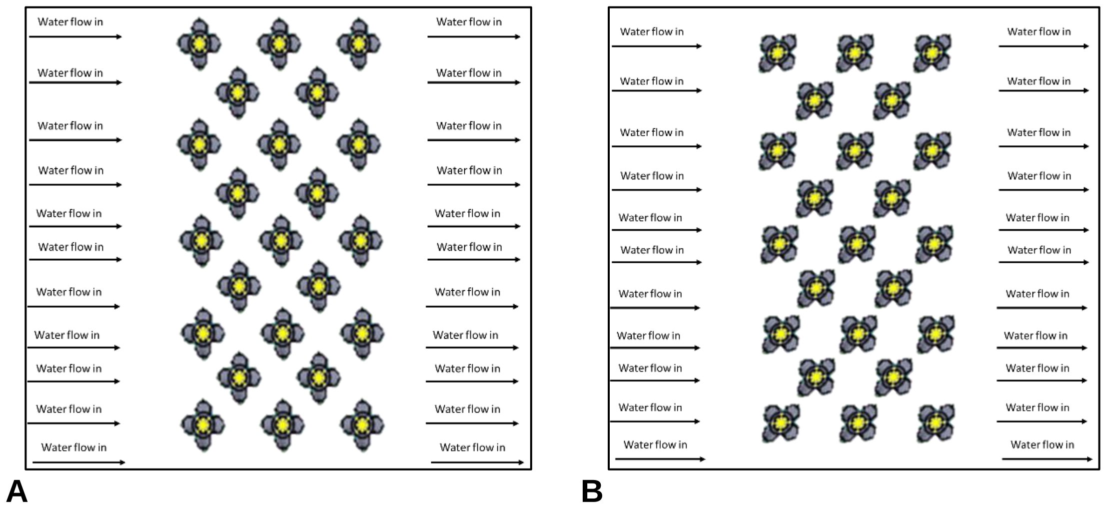


Fig. 2. Intertidal pots were arranged in a zigzag pattern in a) straight angle and b) acute angle

In Scenario 2 (wave), these sections had a wave velocity of 12 m/s with a frequency of 1.0 m depth, and this frequency continued with a fixed intensity at a depth of 1.5 m (*i.e.*, the average height of mangrove trees over 3 months). Because of the limitations in the capability of the computer to run the simulation, 13 intertidal pots were used, as illustrated in Fig. 3.

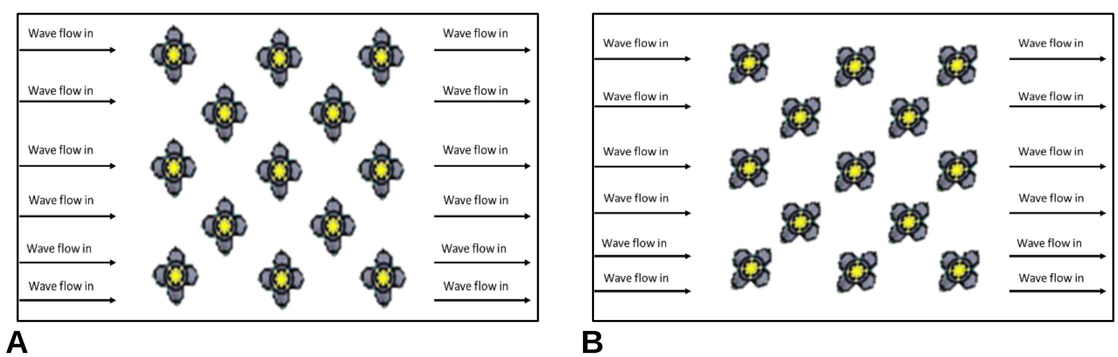


Fig. 3. Intertidal pots were arranged in a zigzag pattern in a) straight angle and b) acute angle

The fluid flow calculation was conducted using both theoretical calculations (Bernoulli's theory) and numerical simulations (Computational Fluid Dynamics) (Jiang 2021; Goteman *et al.* 2022). Bernoulli's theory is related to the conservation of energy in fluids by considering the kinetic energy, potential energy, and fluid pressure. The discharge coefficient (C_d) is an empirical constant used to improve the accuracy of the calculation, depending on the shape of the flow channel. The short-tube flow channel is a type of flow channel with a C_d value of 0.81.

Numerical Simulation: CFD

The volume of fluid (VOF) method is a method of calculating multiphase flow by calculating the volume fraction of liquid and gas in each cell (Garoosi and Hooman 2022). The free surface is the location where the volume fraction of liquid and gas is equal (50%). The transient calculation is the calculation of the change of various quantities with time. The CFD physical modeling creates a solid body: SolidWorks (Dassault Systèmes SolidWorks Corporation, version 2020, Waltham, MA, USA) was used to create a solid body inside the tank.

In the initial condition, the interior of the solid is 100% water and the rest is air. The Bernoulli equation (Eq. 1) was used to calculate the flow rate from the orifice, as follows:

$$Q = C_d * a * \sqrt{2g(H-h)} \tag{1}$$

The equation for the time required to empty the tank can be obtained using Eq. 2:

$$t = \frac{A}{a*C_d} * \left(\sqrt{H-h}\right) * \sqrt{2/g} \tag{2}$$

All information in this section is a requirement of the Solidworks software terms of use, as referenced in the website (Solid Solutions 2020). In the previous equations, Q is the flow rate of water in m^3/s; C_d is the discharge coefficient, which is a constant that depends on the shape of the aperture, and in this case, $C_d = 0.81$; a is the cross-sectional area of the aperture in m^2, 0.0452 m^2; g is the gravitational acceleration (m/s^2), 9.81 m/s^2; H is the water level above the bottom of the tank (m), 2.995 m; h is the center level of the aperture above the bottom of the tank (m), 0.745 m; and A is the cross-sectional area of the tank (m^2), 3.11 m^2. The theoretical calculation (*i.e.*, Bernoulli's equation) predicts a flow rate of 14,429 L/min, whereas the CFD simulation predicts a flow rate of 14,073 L/min, a difference of approximately 3%. Calculating the drainage time, the theoretical calculation predicts a drainage time of 58.2 s, whereas the CFD simulation predicts a drainage time of 59.9 s, a difference of approximately 3%. The results from the theoretical calculations and CFD simulations differ by about 3%, which is considered very close. To examine the relationship between the results from the theoretical calculations and the CFD simulations, the CFD simulations were performed at 10 initial water levels using the "What If" analysis technique. The results from all 10 CFD simulations were plotted and compared with the results from the theoretical calculations. The results of the physical properties showed that the third formula (*i.e.*, 1:3:1) was able to form well, and the highest percentage of degradation was a 50:50 ratio. The findings in this study will be helpful information to manage plastics in the agriculture sector. In addition, a particular amount of fly ash from the energy sector's manufacturing process is being used, thus eliminating waste or adding value.

Total Threshold Limit Concentration (TTLC)

This study measured the total concentration of a specific contaminant in a waste or soil sample using Total Threshold Limit Concentration (TTLC), evaluated the pots for compliance, which regulate hazardous chemical levels in waste materials. These standards are outlined in the Ministry of Industry's 2005 Decree on the disposal of wastes and unused materials (Ministry of Industry 2005). Adherence to TTLC helps prevent the environmental contamination of water, soil, and air.

RESULTS AND DISCUSSION

Characteristics of RWFA

The XRF analysis revealed a high concentration of CaO (38.9%) in the RWFA, with additional components, including K_2O (13.9%) and SiO_2 (11.3%). This was also reported by Sirikunpitak *et al.* (2023). The XRD analysis further confirmed the presence of $CaCO_3$ and SiO_2 as the primary constituents. These findings corroborate previous research (Boonyaroj and Saramanus 2019; Suwunwong *et al.* 2021; Sirikunpitak *et al.* 2023) on the composition of RWFA. The high CaO content imparts strong alkaline properties and provides essential plant nutrients. Plant Nutrients; Organic Matter 8.9%, Total K_2O 8.8, Total P_2O_5 1% and Total N 0.006%, which was proposed in earlier study (Sirikunpitak *et al.* 2023). Several studies have demonstrated the potential of RWFA as a beneficial soil amendment for improving soil quality and addressing nutrient deficiencies (Borno *et al.* 2018; Ultra *et al.* 2024).

Characteristics of Sand and Clay

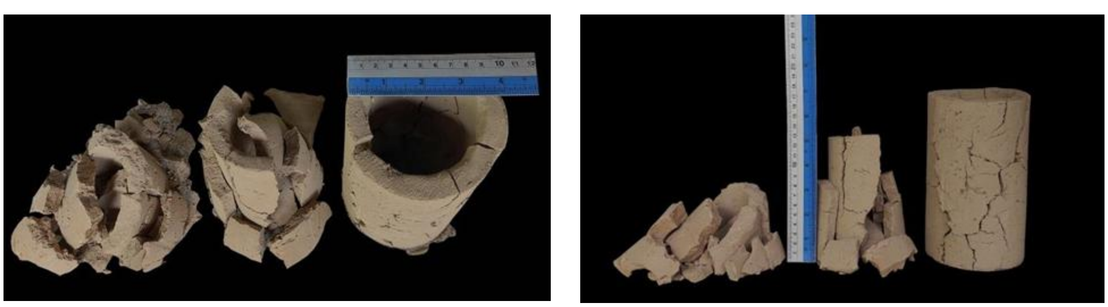
Grain size distribution data were collected from the Kantang Silviculture Research Station, as shown in Table 1. The results of the study were found to be consistent with Bunyavejchewin and Nuyim (1998), who collected samples in the Tura Island area, which is in the vicinity of the Kantang Silviculture Research Station, which provided muddy soil. It is also consistent with the geological map, which indicated that the area is made up of tidal flat deposits and some alluvial fan deposits consisting of gravel, sand, conglomeratic sand, and dandy silt, which are fine to coarse grained and angular (Department of Mineral Resources Ministry of Natural Resources and Environment 2007).

Table 1. Grain Size Distribution from Kantang Silviculture Research Station

Sample	Grain Size Distribution (%)				Gravity of Soils (g/m^3.cm)	Color	Types of Soils
	Gravel	Sand	Silt	Clay			
Sand	10.54	65.62	7.63	16.22	2.39	Pale grey	Clayey sand with gravel

Ratio for the Development of Seedling Pots

The results of the physical forming of the seedling pots were analyzed by visual inspection. The RWFA, sand, and clay ratios of 3:1:1 (Sample A), 2:2:1 (sample B), and 1:3:1 (sample C) were determined, as illustrated in Fig. 4.



a b c a b c

Fig. 4. Seedling pots by visual inspection in a) Sample A, b) Sample B, and c) Sample C

The proportions used were based on the work of Michael (2016), which is an easy-to-experiment material synthesis method. This formula is widely used as a mixing method to compare the various effects on ceramic surfaces.

Sample A with the RWFA, sand, and clay ratio of 3:1:1 was shaped according to the model with only 30% stability from the damage pot when compared with Sample C based on the stability of the seedling pots. When Sample A was dried in the sun, cracks appeared and could not be repaired.

Sample B with the RWFA, sand, and clay ratio of 2:2:1 was shaped according to the model. However, on the fourth day of sun drying, 50% of the clay began to crack. Therefore, Sample B was placed back in the oven. However, after baking, more cracks appeared.

Sample C with the RWFA, sand, and clay ratio of 1:3:1 was shaped according to the model with 70% stability. When the pots were placed in the oven, the pots became more stable and stronger but still had the same cracks as before being placed in the oven.

The aforementioned results indicated that Sample A had the highest proportion of fly ash, followed by Samples B and C with the least. As a result, the seedling pots formed by Sample A had severe cracks and excessive shrinkage. Because the wood ash particles are small and have a specific surface area, they absorb more water. When dry, severe cracks loss of strength, and excessive shrinkage occur. (Huang *et al.* 2021; Verma *et al.* 2023; Akinwale *et al.* 2024). The results of the study showed that the proportion of Sample C could be shaped better than the other proportions.

The results of the study further showed that the proportion of Sample A could be shaped better than the other proportions. This design was inspired by the (1) roots of mangrove trees, (2) the Sta-Pod, and (3) a tetrapod, was designed similarly to coastal engineering structures to prevent wave erosion (Smith 2016), as illustrated in Fig. 5, consistent with previous work that reported that mangrove-inspired wave barriers are effective in reducing coastal erosion (Phuoc and Massel 2006; Lee *et al*. 2021).

a b c

Fig. 5. Intertidal pot

Simulation of Seedling Pot Interactions

This study involved two experimental cases designed to compare the effectiveness of the a) straight angle and b) acute angle pot placements. The study results showed the change in the depth of the water level and the speed of the water flowing through the pot placement and observed the breakup and release of energy from the waves. However, this finding only emphasized the attenuation of the waves or the fact that the energy of the waves is affected by the change in water speed, *i.e.*, dissipating when the waves move through the pot placement, assuming that the water depth is constant throughout the pot placement and does not consider the impact due to water currents, *i.e.*, when the water flows through the pot placement, the water speed will decrease (Vieira *et al.* 2020; Scardino *et al.* 2022).

Scenario 1: The case of water flowing at a constant speed

The straight angle pot arrangement, which was tested at a water depth of 0.25 m and a velocity of 0.25 m/s, resulted in a consequential reduction in the water velocity as it flowed through the pots. The water level impacted the pot legs, causing a decrease in velocity to less than 0.25 m/s after the first row.

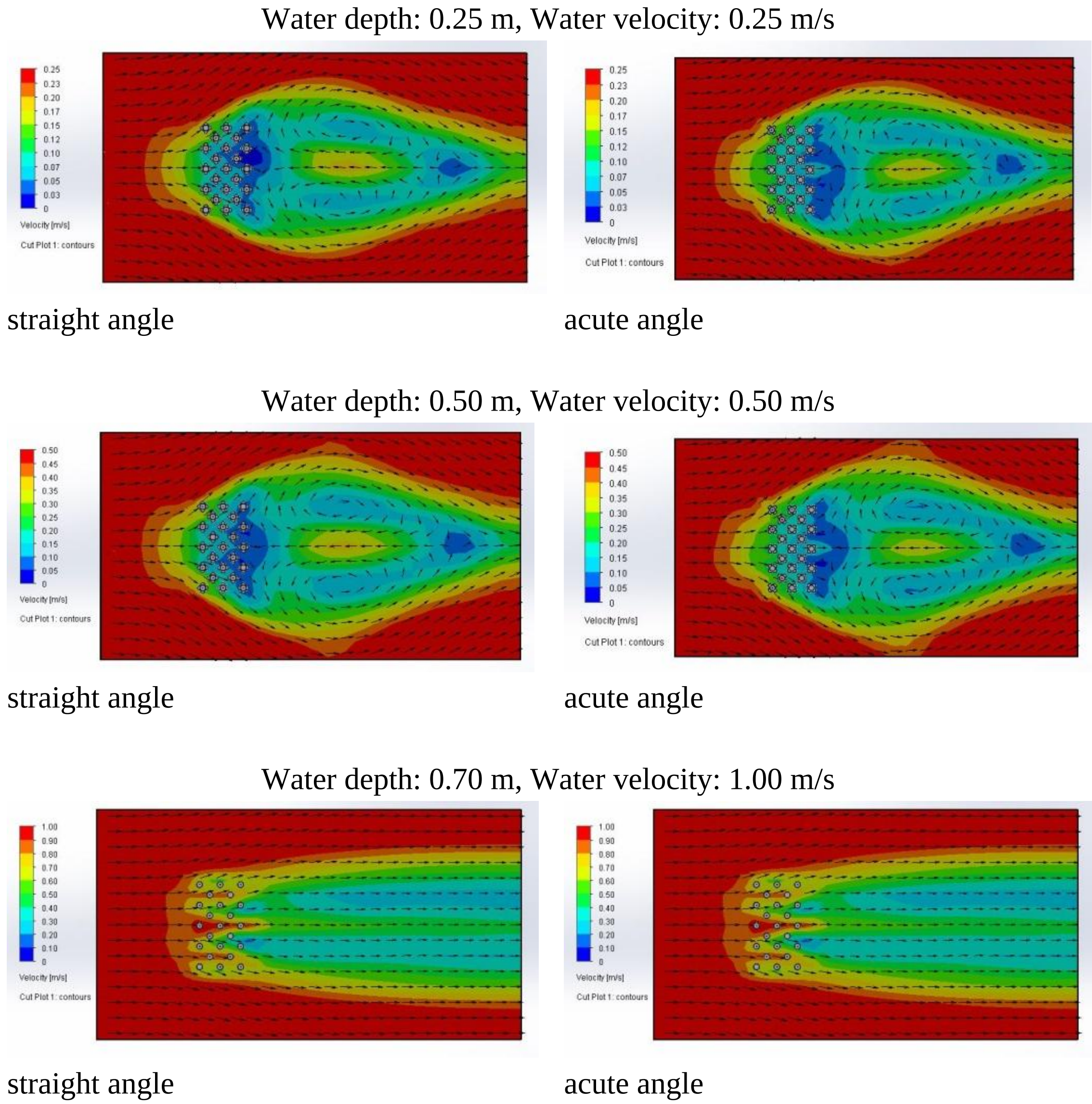


Fig. 6. Simulation of seedling pots interactions

After passing through all five rows, the water velocity approached zero, leading to a reversal of the flow direction and swirling around the pots. In contrast, a 45° pot arrangement at a water depth of 0.50 m and a velocity of 0.50 m/s maintained a more consistent water velocity distribution. However, increasing the water depth to 0.70 m and the velocity to 1.0 m/s in Case 2 did not alter the pattern of velocity reduction, as the water level covered all four pot legs and impacted the pot necks. This resulted in a decrease in the velocity from 1.0 m/s to less than 0.20 m/s, as illustrated in Fig. 6. This is consistent with Boulet *et al.* (2018) and Williams *et al*. (2018) who stated that when a wave moves through a wave breaker, its speed will decrease because of the energy transfer.

Scenario 2: The case of an incoming wave

In the model, the X-axis represents the distance, Y represents the water depth, and Z represents the pot position. The color bar indicates the wave speed at each location. As the waves collide through the pot line, their speed decreases notably, as illustrated in Fig. 6.

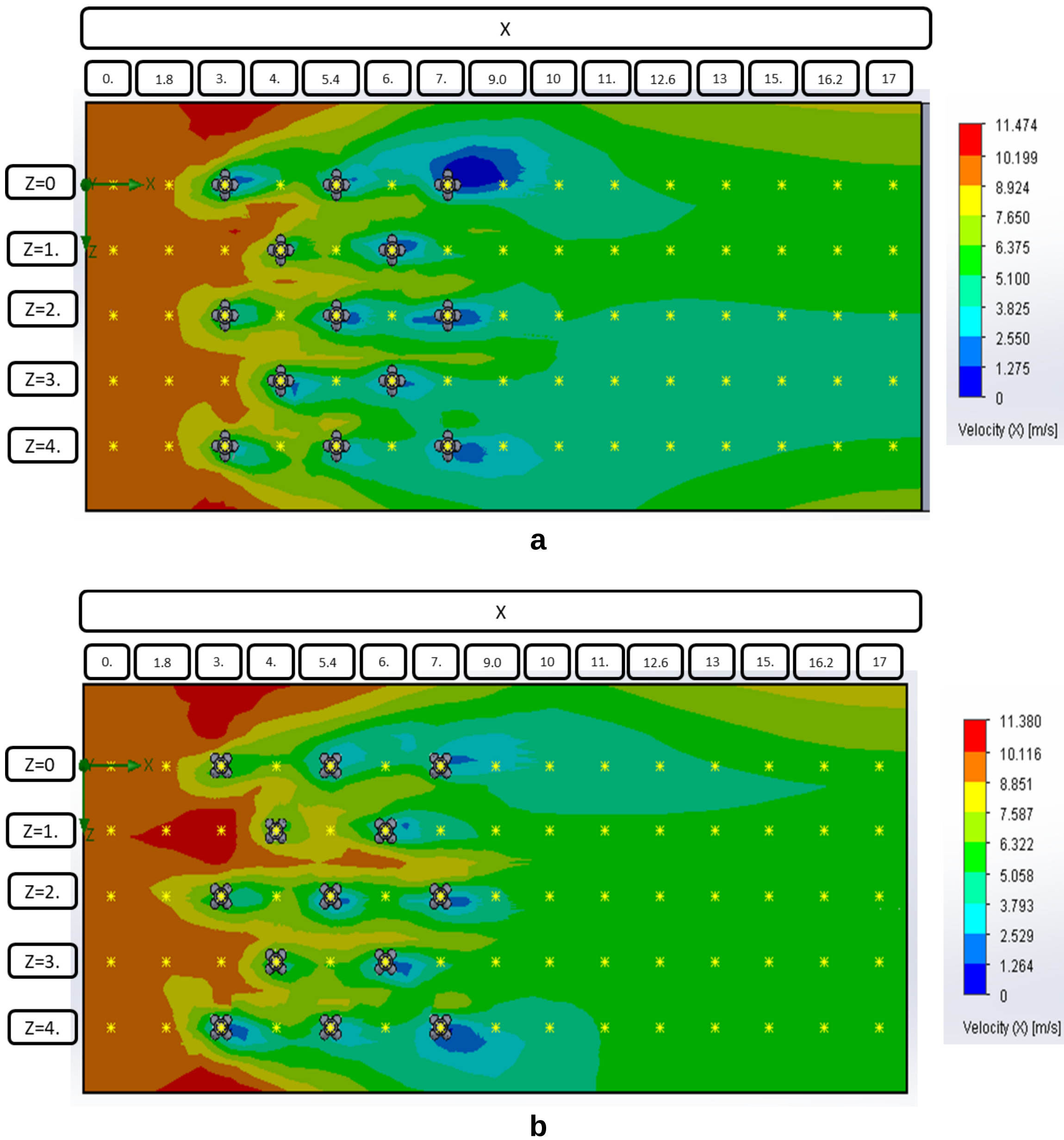


Fig. 7. Simulation of seedling pot interactions: a) straight angle and b) acute angle

For instance, in a straight angle, the wave speed drops from 9.7 to 1.4 m/s between positions 3 M and 7.8 M, nearly stopping. Conversely, when the waves move away from the pot line, their speed increases more rapidly but remains lower than the original speed due to the zigzag pot layout. Consequently, areas without pots exhibit higher wave speeds, as indicated by the color bar in Fig. 7. The results of this study are consistent with Scenario 1, where the wave speed decreases when passing through the pot line.

From the results of both scenarios, it was found that the velocity vector changed direction upon contact with the wave breakers and accelerated laterally on the side of the structure (EMODnet 2020; Thomas 2022). This allowed the authors to confirm the risk of erosion in the unprotected zone by comparing the seafloor current velocities with and without the wave breakers at different locations. If the structure slows down the currents in general around and after them, then the energy is dissipated and not reflected, which will not increase erosion in the unprotected area.

TTLC Method

Table 2 presents the calculated concentrations of various hazardous substances in the ash sample, measured in mg/kg. Upon comparison with established standards (Ministry of Industry 2023), all detected hazardous substances were found to be below the permitted limits. Consequently, the ash sample was deemed to pose no crucial environmental risk.

From the standard TTLC test results and other additional factors, such as the solidification process and the appropriate solvent pH, it can be concluded that the tested pot is environmentally safe in terms of leachate leakage because toxins are fixed in the solidification process, causing the toxins to be fixed in the material and cannot easily move to contaminate the environment. In terms of low toxicity and solubility, the appropriate solvent pH causes fewer toxic substances to dissolve, resulting in a small number of leaked toxic substances. In terms of low risk of contamination, when the pot is buried or disposed of, the toxins will not leak out to contaminate groundwater, soil, or air, and hence, the proposed pot does not cause any impact on the environment. This is consistent with the findings of Suwunwong *et al.* (2021).

Table 2. TTLC Method

Sample	TTLC						
	As	Cd	Cr	Cu	Pb	Ni	Mn
	≤ 500 mg/kg	≤ 100 mg/kg	≤ 2,500 mg/kg	≤ 2,500 mg/kg	≤ 1,000 mg/kg	≤ 2,000 mg/kg	mg/L
RWFA	0.76	0.12	2.51	27.79	0.94	18.03	1,112
Seedling Pots Sample A	1.86	0.08	2.61	9.53	1.05	7.95	535
Seedling Pots Sample B	1.49	0.08	2.90	21.23	0.52	15.68	967
Seedling Pots Sample C	1.14	0.08	2.64	23.91	0.22	17.99	1,063

Implications

Mangrove planters specifically designed for mangrove restoration must consider several important factors. The design must be consistent with the local environment, including proximity to tourist attractions and the diversity of surrounding trees. The materials used should be biodegradable to support the natural growth of mangrove seedlings. The structural design of the planters must adequately support *R. apiculata* seedlings throughout their 90-day growth period. To increase community participation, the planters should be designed to encourage tourists to participate in planting mangrove seedlings. Mangroves are important ecosystems along tropical and subtropical coastlines, and they provide a wide range of ecological functions and benefits, such as coastal stabilization, wave attenuation, and coastal erosion reduction. The dense root systems of mangrove trees help to anchor the soil and reduce the impact of waves and currents protecting coastlines from erosion. biodegradable nursery pots, which can manage fly ash and reduce the use of seedling bags. and can also help reduce the speed of water currents and waves. From the model, it was found that placing the pots in straight angle gives better results than acute angle. It also makes use of waste from the energy sector and increases forest areas, reducing coastal erosion. Recommendation includes testing this model in actual areas. Intertidal pots made from rubberwood ash can be used because they contain primary and secondary plant nutrients. The test results have shown that they do not affect the environment. Therefore, they are suitable for use. Suggestions include studying and comparing the use of fly ash from other types of fuel and adjusting the ratio to make it more refined.

CONCLUSIONS

This study proposed using rubber wood fly ash (RWFA) to create environmentally friendly seedling pots to help in mangrove restoration. From the results of the study, the following conclusion can be drawn:

1. Sample C with the RWFA, sand, and clay ratio of 1:3:1 could be shaped according to the model, both before and after heat treatment. However, the formulation resulted in cracked pots. Recommendations include investigating in more detail the ratio and the option of using binders, such as glue, latex, and cassava starch, as well as the use of different temperatures to assess the stability and digestion of planting containers.

2. The results of the study of the pot placement pattern in the model determined that placing the pots at a straight angle yielded better results than at an acute angle. Based on the modeling analysis, the water velocity changed and decreased when passing through the pot line, which can help reduce the speed of the water (*i.e.*, the case of water flowing at a constant speed in Scenario 1 and the case of an incoming wave in Scenario 2). Recommendations include that the created pots should be tested for planting mangrove trees and placed in the actual area to compare the values with the results obtained from the model.

3. The results of total threshold limit concentration (TTLC) show that the tested pot is environmentally safe in terms of leachate leakage because toxins are fixed in the solidification process and the detected values are lower than the standard criteria. Furthermore, the leaching results indicate that the TTLC toxicities of RWFA were lower than the limits for unused materials, which are nonhazardous waste.

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