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Potential Use of Biomass Waste as a Sustainable Energy Source in the Future: A Case Study

Siriphat Sirikunpitak [1], Issara Chanakaewsomboon [2], Anil Kumar [3], Apichat Choomkong [4], Asad Ullah Baoch [5], Kuaanan Techato [1]

[1] *Sustainable Energy Management Program, Faculty of Environmental Management, Prince of Songkla University, Thailand*
[2] *Sustainable Innovation Center (SIC-PSU), Faculty of Environmental Management, Prince of Songkla University, Thailand*
[3] *Department of Mechanical Engineering, Centre for Energy and Environment, Delhi Technological University, Delhi, India*
[4] *Kantang Silviculture Research Station, Trang, Thailand*
[5] *Department of Chemical Engineering, Faculty of Engineering and Architecture, Balochistan University of Information Technology, Engineering & Management Sciences – (BUITEMS), Quetta, Balochistan, Pakistan*

Abstract **– Mangroves have been degraded and converted for decades due to a multitude of factors, ranging from human activity to natural perturbations such as disasters and global warming. Experiments were conducted to determine the impact of fly ash (FA) on the growth of Rhizophora apiculata Blume's (R. apiculate). A completely randomised design (CRD) was employed with D as the control, and nine treatment soil amendments were created from abandoned shrimp pond sediment with rubberwood fly ash (RWFA). These amendments were made by mixing three separate FA samples (A, B, and C) in the ratios of 75:25, 50:50, and 25:75, respectively (A1-A3, B1-B3, and C1-C3), using a total of 200 R. apiculata specimens.**

The experiment revealed that the addition of FA and its combination had a significant effect on promoting the growth of R. apiculate and improved nutrient availability and retention in the soil. The results of the experiment demonstrate that the effect of Fly Ash (FA) and its combination significantly influence the growth of *R. apiculate*, impacting the total heights and number of leaves. The most beneficial effect the results of the experiment demonstrate that the effect of fly ash (FA) and its combination significantly influence the growth of R. apiculate, affecting the total height and number of leaves. The most beneficial effects were observed when the optimal proportion of each type of soil amendment was used. The study holds substantial benefits: it introduces a method for improving the soil of shrimp farms through the utilisation of rubberwood fly ash (RWFA) and serves essential nutrients to mangroves. Moreover, implementing this plantation technique can aid in protecting against coastal erosion.

Keywords **– Rubberwood ash, potting soil, mangroves, mangrove restoration, soil amendment.**

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Corresponding author: Kuaanan Techato,
Faculty of Environmental Management, Prince of Songkla University, HatYai-90110, Songkhla, Thailand
Email: kuaanan.t@psu.ac.th

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1. Introduction

Around 137,760 km^2 of mangrove forests are found in 118 different countries; the largest portion, or 42%, is in Asia, followed by roughly 11% in South America, 12% in Oceania, 15% in North and Central America and 20% in Africa [1]. They have been dispersing in the intertidal or tidally-influenced zone, spanning 60% to 75% of tropical coastlines [2], [3]. Mangrove forests sustain aquatic and coastal food networks in addition to storing enormous amounts of carbon [4], [5].

Additionally, they decrease the effects of calamities like storms, tsunamis, and coastal erosion [6]. However, due to both natural and human activities [7] such as shrimp farming, logging, charcoal manufacture, oil exploration and extraction, tourism, and land-use change, mangrove forests are currently suffering from considerable degradation [8], [9] Aside from area loss and pollution, growing urbanization, agriculture, industry and aquaculture are the main causes of mangrove decline. Now mangroves are being lost at a frightening rate throughout the world. as a result of human-caused activities [10] Mangrove losses reach 2-5% of yearly forest area in various countries [11] Deterioration and destruction are predicted to occur at a rate of about 1% per year. An estimated 20 to 35% of mangrove forests worldwide have disappeared since 1980. The growth of shrimp and salt farms caused Thailand to lose over 56% of its mangrove forests between 1961 and 1996 [12].

Mangroves are prominent in Thailand, predominantly found in muddy tidal flats, especially along the Gulf of Thailand; they are also densely populated along the Andaman Sea. The soil within mangrove forests is typically unripe, or entisol, composed predominantly—about 90%—of microscopic clay particles. This soil exhibits colors ranging from grey to dark reddish-brown, referred to as laterite, and its pH tends to be neutral to alkaline (basic)[13]. In various mangrove forests, the composition of soils includes less than 45%, 40%, and 35% of clay, silt, and sand, respectively [14], [15], [16]. However, it is noteworthy that mangrove forest soils in various countries predominantly exhibit a clay loam texture. Mangrove forests are susceptible to alterations from their natural state due to multiple factors such as infrastructure development, land-use change, global climate change, and the expansion of aquaculture activities. These modifications often result in soil degradation and contribute significantly to pollution within these ecosystems [17].

Mangrove rehabilitation and restoration projects are typically created and implemented as "one-off" undertakings, with a startlingly low emphasis placed on sharing important knowledge about past successes and failures or technical expertise that could help projects succeed [18], [19] Unsurprisingly, there is still an unacceptably high failure rate for mangrove rehabilitation and restoration initiatives [20], [21]

Ash as solid biomass is typically challenging to use in combustion systems because of its disparate physical and chemical characteristics [22], [23]. For nutrient addition and pH raising, wood ash has a long history of usage as a soil supplement in agriculture, and wood is a raw earth that is widely available and environmentally friendly [24].

According to studies on the subject, wood ash can be utilized in agriculture in three different ways: as a source of plant nutrients, as a component in planting material, and as a soil additive in the form of Fly Ash (FA). These methods can enhance the rate and volume of nutrient absorption by plants. Employing the beneficial characteristics of FA can significantly improve soil condition [25], [26].

One approach that can be used widely to improve coastal safety is mangrove regeneration. The rehabilitation of the area is also being assisted by several government, Nongovernmental organizations(NGOs), the private sector, and students, involved in the area's rehabilitation, especially through the coordinated planting of mangrove trees. Seeds (propagules) were used [19]. However, the survival rates of planting attempts failed. When planting is suggested as a method of survival [27], [28] there is a risk of impeding natural succession because planting with pods has the drawback that, when flooded, the top will be eaten by predatory animals, leading to a reduced survival rate. Fungi and other bacteria will contribute to the mangrove forest's failure to recover as intended [29], [30] Therefore, this work develops a hypothesis to address the objective of raising mangrove tree survival rates while reducing the amount of FA. With the study of physical components and soil chemistry, RWFA for planting soil, and the feasibility of making a container for planting mangroves, the direct benefit that can be expected is to deal with the problem of FA content and increase the value of FA. The indirect benefit is expected to be an effective increase in the mangrove area, leading to a rich mangrove ecosystem.

This study formulates a hypothesis aimed at achieving dual objectives: enhancing the survival rates of mangrove trees and mitigating the quantities of Fly Ash (FA). By investigating the physical constituents and chemical properties of soil and exploring the suitability of Rubber Wood Fly Ash (RWFA) as a planting medium and a potential material for mangrove planting containers, this work seeks to address issues related to FA content and augment the value derived from FA. The anticipated indirect benefit of this approach is a potential expansion of mangrove areas, fostering a more robust and diverse mangrove ecosystem, in addition to addressing the direct benefits related to FA management.

2. Materials and Methods

In this segment, a systematic methodology was employed to collect and analyze data pertinent to rubberwood fly ash and soil samples.

The chosen samples were scrutinized to deduce valuable insights into their compositions and interactions.

Additionally, a case study was meticulously selected from Trang Province, Thailand to complement the research and provide a real-world context to the theoretical and empirical analyses conducted. Below is a succinct overview of the methodology and methods applied in this study.

2.1. Rubberwood Fly Ash (RWFA) Collection and Analysis

Three samples of PRWFA were procured, with one originating from a biomass power plant in the Songkhla province, and the other two from the Yala province, situated in Southern Thailand. The collected PRWFA directly results from the combustion of rubber wood, occurring at a temperature of 800 °C. Prior to chemical evaluation, a 2 mm sieve was utilized to screen all the PRWFA samples. The chemical compositions of RWFA, including components such as silicon dioxide (SiO_2) and calcium oxide (CaO), were determined utilizing a standard procedure as outlined by a PW2400 X-ray fluorescence spectrometer (Philips, Malvern, UK). Leaching studies employing both the Total Thermodynamic Limit Concentration (TTLC) and Soluble Threshold Limit Concentration (STLC) were conducted to assess the environmental impacts arising from the usage of FA, examining elements like As, Cd, Cr, Cu, Pb, Ni, and Mn.

2.2. Soil Sample Collection and Analysis

Soil samples were collected from an abandoned shrimp farm situated in the Kantang Tai Subdistrict, Kantang District, Trang Province, Thailand. Sampling was conducted at a depth ranging from 0 to 15 cm. The acquired samples were then sieved to ensure particle homogeneity and were meticulously cleared of any unanticipated organic components. Post-sieving, the soil was stored for subsequent utilization in the experimental procedures and was transported to a laboratory where extensive analyses were externally performed by the testing and center of measurement and standard accreditation, faculty of science, Prince of Songkla University, Hat Yai, Thailand. The analyses were executed to determine various soil parameters, including soil pH, extractable N, P, K, organic matter (OM), degradation of organic fertilizer (DOF), NaCl, and Electrical Conductivity (EC), employing In-House methods based on AOAC 20th edition, 2016, and OMAF, 1987.

2.3. Description of the Study Area

The study unfolded at the Kantang Silviculture Research Station (7°21′43.19″N 99°30′29.78″E), specifically within an office nursery adjacent to the mangrove forest in Trang (Figure 1). The designated site is nestled beside the Kantang River, approximately 29 km kilometers south of Kantang District. It spans an area of roughly 4,800 square meters, with Kantang Municipality and Bang Pao Subdistrict Administrative Organization to the north and the Andaman Sea to the south. The regional climate predominantly experiences two seasons: summer, spanning from February to May, and the rainy season, occurring from May to August. In February, the region observes an average temperature of 28.3°C and receives an average rainfall of 1,943 millimeters [31].

2.4. Experimental Treatments

These studies are to assess the effects of RWFA on the growth of R. apiculate and soil properties compared to different fly ash. As indicated in Table 1, the trials were conducted using a completely randomized design (CRD) approach, where each set was mixed in accordance with the predetermined ratio. Twenty duplicates of the tests were run, each with ten treatments, including (D control) A1-A3, B1-B3, and C1-C3, using a total of 200 R. apiculata. Each replica was placed in a 3x7-inch plastic pod, which received daily watering of seawater with a salinity of 30 ppt for three months.

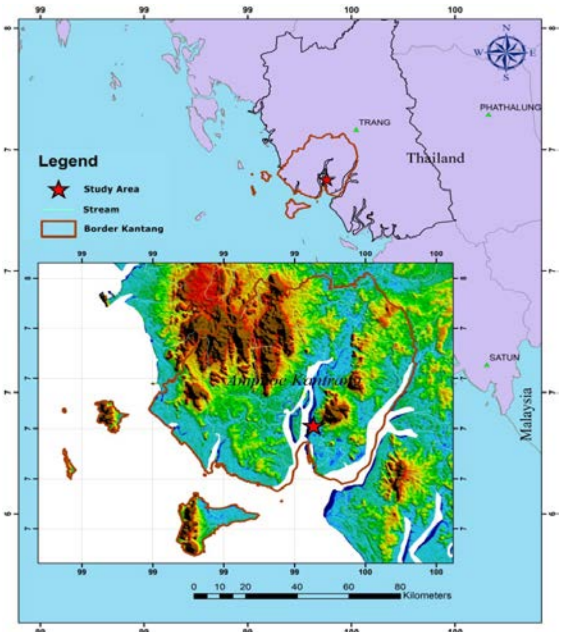

Figure 1. Study area in *Kantang Tai Subdistrict, Kantang District, Trang Province*

Table 1. Experimental treatments

Experimental	Treatments	Ratio soil: fly ash %(w/w)	
		Soil	Fly ash
	A1	75	25
1	A2	50	50
	A3	25	75
	B1	75	25
2	B2	50	50
	B3	25	75
	C1	75	25
3	C2	50	50
	C3	25	75
4	D	4	-

2.5. Observation of the Parameter

The research parameters were diligently observed every week for a period of three months during the development phase of R. apiculata, as illustrated in Figure 2. The parameters include:

a) Measurements of plant height from initiation to conclusion, taken at the base of the stem, specifically above the swelling where the propagule intersects with the emerging stem.

b) The comprehensive count of leaves developed on each plant throughout the study period.

2.6. Characterization of Rubber Wood Fly Ash and Soil

Table 2 presented, detail the variations in the chemical properties of the ash, generated from two distinct samples of Rubberwood Fly Ash (RWFA), illustrated in Figure 3.

Figure 2. Measurements and observations.

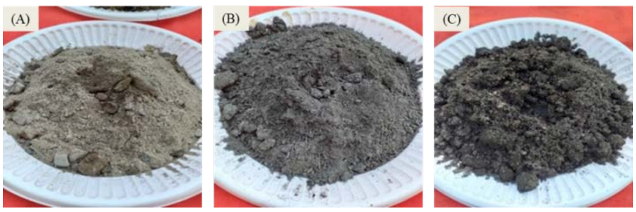

Figure 3. Rubberwood fly ash (RWFA)

Table 2. Rubber wood fly ash chemical composition

Elements	**Chemical composition**		
	A	**B**	**C**
Na_2O	0.099	0.161	0.046
MgO	6.534	7.956	5.314
Al_2O_3	0.85	1.09	1.406
SiO_2	9.551	11.275	13.849
P_2O_5	2.62	2.788	2.799
SO_3	1.167	0.965	0.983
Cl	0.108	0.034	0.047
K_2O	8.068	13.867	5.984
CaO	35.948	38.863	34.202
TiO_2	0.078	0.1	0.106
MnO	0.605	0.896	0.635
Fe_2O_3	0.612	0.915	0.824
NiO	0.01	0.017	0.016
CuO	0.016	0.015	0.019
ZnO	0.059	0.027	0.083
Rb_2O	0.044	0.064	0.034
SrO	0.113	0.133	0.12
BaO	0.034	0.042	0.054
PbO	0.004	N	0.008

Figure 4. Abandoned shrimp farm soil

Table 3. Initial soil conditions (0–15 cm) of sample

	Sample
pH	8.35
Total N % (w/w)	0.022
Total P_2O_5 % (w/w)	0.04
Total K_2O % (w/w)	0.01
OM % (w/w)	0.95
DOF % (w/w)	28.02
NaCl % (w/w)	0.06
EC (ds/m)	0.02

2.7. Rhizophora Apiculata Seedlings

Rhizophora apiculata (R. apiculata) stands as the prevailing plant species within the Kantang Silviculture Research Station. It is advisable to collect the propagules subsequent to their detachment from the tree.

Specifically, the selection of propagules is recommended to be meticulous, prioritizing those that manifest a healthy appearance and exhibit no signs of damage from borers or crabs.

2.8. Statistical Analysis

Both qualitative and quantitative data were collected for the purpose of this study. The examination of qualitative data involved descriptive analysis. Statistics tests were utilized in analyses of quantitative data. The statistical results (ANOVA) were obtained using factoritorial designs, test analyses, and ANOVA. When the Anova test showed a significant effect of treatment, the Tukey test ($p < 0.05$) was used to show a significant difference.

3. Results and Discussion

In this section, we explore the results and interpretations obtained from a thorough analysis of the chemical characteristics of Rubberwood Fly Ash (RWFA) and its significant effects on the growth and development of R. apiculata. Ash from different RWFA samples was carefully examined and its effects on soil and plant components. Table 2 and Figure 3 show how RWFA may assist agriculture by affecting plant height and leaf growth. Furthermore, the nuanced discussions aim to incorporate the observed outcomes with pre-existing knowledge, thereby offering a comprehensive comprehension of the role of RWFA in augmenting agricultural productivity and sustainability. The ash's chemical characteristics and their complex interaction with plant and soil dynamics are carefully examined, highlighting RWFA's potential for agricultural improvement and environmental conservation.

3.1. Effects of Amendments on the Characteristics of Soils

The incorporation of PRWFA instigated alterations in both the physical and chemical properties of the soil, in alignment with the impacts of amendments on soil characteristics. The findings reveal that the application of PRWFA induced variations contingent upon the type of soil amendment employed (Table 4); where sample D represents abandoned shrimp farm soil, and samples A, B, and C represent PRWFA (for detailed information, refer to Table 1 in the supplementary material). Notably, the rate of application of fly ash compost yielded soils exhibiting significant disparities amongst each other. The characteristics of ash in agricultural soils are subject to variations, influenced by soil type, plant species, and the origin and nature of ash [32], [33] , underscoring the need for effective management strategies for ash utilization in agriculture.

The outcomes indicate that the parameters such as pH, total nitrogen, and available phosphate experienced substantial elevations post-PRWFA application. In comparison to sample D, all soils subjected to PRWFA amendments exhibited elevated levels of extractable total potash. To assess the effective management of ash in agriculture, meticulous examination and analysis were undertaken. The findings demonstrate that following the integration of PRWFA, there was a significant elevation in the levels of pH, total nitrogen, and available phosphate of the soil amendments. When benchmarked against sample D, every soil variant treated with PRWFA amendments exhibited augmented levels of extractable total potash. [34], [35] demonstrated that using ash in agriculture can improve soil quality and yield. The effectiveness of the fly ash-based potting soil experiment revealed a significant change in soil performance. Fly ash affects the properties of the soil used to grow mangroves in terms of pH, total N, total P_2O_5, total K_2O, OM, DOF, NaCl, and EC. The ratio of fly ash addition significantly affects soil properties, consistent with Gagnon *et al.*, [36]. That is, the addition of ash to the soil increases its pH, in line with Simard *et al.*,[37]. It is acidic and neutral because fly ash contains hydroxide compounds and carbonate hydroxides of alkali metals. It dissolves in water to release hydroxide ions, neutralizing soil acidity it was found consistent with the research [38]. The pH value is very important for the change in soil chemistry because it affects the solubility of various elements or nutrients. Providing plants with nutrients such as S, B, and Mo in beneficial ways increases the nutrient status of the soil. The addition of fly ash improves porosity and water retention capacity . As a result, loose soil is formed [39]. The addition of wood ash was mentioned as adding CaO, total K, and total P to increase plant biomass. Despite the fact that the nitrogen concentration in the ash was low, it was used to improve the soil. This may be because the ash stimulates organic matter in the soil. Soil electrical conductivity is a metric for salt content in soil (soil EC). Salinity is a major factor in determining soil fertility which affects a plant's productivity, plant compatibility, plant nutrient availability, and essential soil processes that are impacted by soil microbes. Oversalting the soil hinders plant development by upsetting the equilibrium of the soil and water. Oversalted soils are a natural result of arid environments.

3.2. Effect of Soil Amendments and Rubber Wood Fly Ash on R **Apiculata** *Seedling Growth*

According to a study, the effects of planting soil with RWFA ash on the growth of *R.* apiculata seedlings were positive (Figure 5).

Using fly ash to enhance soil compared with the control trial, there were more studies demonstrating trends in budding time, height, and leaf count (Figure 4). The application of soil amendments significantly improved R. apiculata plant growth compared to that in the control. The research's findings were divided into two sections: the duration section and the growth section with information on the growth measurement.

Table 4. Characteristics of soil amendments applied

	Sample			
	A	A1	A2	A3
pH	13.78	11.09	10.98	11.84
Total N % (w/w)	0.043	0.019	0.021	0.015
Total P_2O_5 % (w/w)	1.15	0.35	0.46	0.87
Total K_2O % (w/w)	6.15	0.1	1.86	4.69
OM % (w/w)	12.38	4.16	4.62	11.03
DOF % (w/w)	88.68	37.25	24.88	68.48
NaCl % (w/w)	0.18	0.16	0.16	0.17
EC (ds/m)	9.68	3.23	2.63	11.84
	Sample			
	B	B1	B2	B3
pH	13.11	12.33	12.9	13.01
Total N % (w/w)	0.006	0.017	0.005	0.005
Total P_2O_5 % (w/w)	1.06	0.33	0.79	0.92
Total K_2O % (w/w)	8.81	2.67	7.33	8.41
OM % (w/w)	8.90	3.43	6.46	8.97
DOF % (w/w)	88.89	23.15	42.17	68.05
NaCl % (w/w)	0.09	0.06	0.08	0.1
EC (ds/m)	19.54	6.223	13.89	17.83
	Sample			
	C	C1	C2	C3
pH	10.94	10.62	11.27	11.44
Total N % (w/w)	0.039	0.046	0.075	0.069
Total P_2O_5 % (w/w)	1.37	0.2	0.38	0.43
Total K_2O % (w/w)	5.18	1.5	3.31	4.15
OM % (w/w)	19.96	4.97	9.51	15.12
DOF % (w/w)	68.76	31.4	56	46.98
NaCl % (w/w)	0.09	0.14	0.3	0.37
EC (ds/m)	5.61	2.58	6.47	12.84

3.3. The Survival Effect of Mangrove

Figure 5 shows the relationship between the mean growth of mangroves to potting soil and the time to test the effect of potting soil efficiency. There are four stages in total: starting, first couple sprout, 2 leaf budding, and 4 leaf budding. The experimental plan showed that types of A, B, and C fly ash affected the growth. In Figure 5, sprout with 2 and 4 leaves are seen, followed by A1–A3, B1–B3, and C1-C3 after 2 and 3 weeks, respectively, but the mangrove pods in control D have not changed in 5 weeks, yet they remained in the same shape.

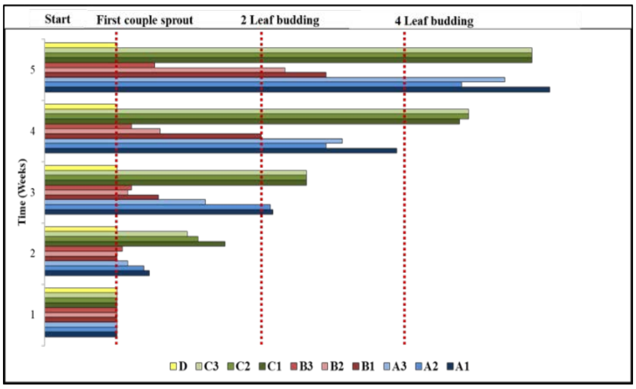

Figure 5. Survival effect of mangrove

3.4. The Growth Rate of Mangrove

Figure 6 shows the results of comparing mangrove growth induced by various planting soil nutrients. The growth results demonstrated that the height of the mangroves is influenced by the rate of PRWFA addition, depicted in Figure 6. After 8 weeks, the height of control D started to increase, and the generated soils C1-C3, and A1–A3 showed greater growth than the B1–B3 series.

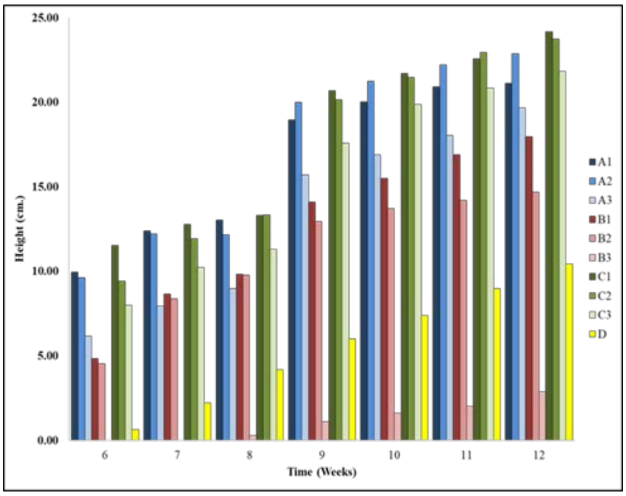

Figure 6. The height of R. apiculate *with respect to time*

Table 5. Comparison o R. apiculate *heights after 12 weeks in samples A1-A3*

Sample	N	Mean	S.D.	F	P
A1	20	21.10	5.550		
A2	20	22.88	4.292	1.878	0.162
A3	20	19.67	5.902		

Table 5 shows a comparison of R. apiculate heights after 12 weeks in samples A1-A3, classified by proportion. There was no statistically significant difference at the 0.05 level ($p > 0.05$).

Figure 7. Different Stages of the growth of R. apiculate

Table 6. Comparison of mangrove highs after 12 weeks in samples B1-B3

Sample	N	Mean	S.D.	F	P
B1	20	17.95[a]	5.299	52.027	0.000*
B2	20	14.68[b]	6.066		*
B3	20	2.88[c]	3.255		p≤0.05

In Table 6, the comparison of the heights of mangroves at 12weeks in samples B1–B3 was classified by proportion. There was a statistically significant difference at the 0. 05level (p< 0.05), with the highest proportion being B 1(17. 95cm), followed by B2 (14. 68cm), and B3 (2. 88cm), respectively, and from the pair test, it was found that there were 3 different pairs, namely B 1and B2, B 1and B3, B2, and B3.

Table 7. Comparison of R. apiculate *heights after 12 weeks in samples C1-C3*

Sample	N	Mean	S.D.	F	P
C1	20	24.17	5.198		
C2	20	23.73	3.972	1.444	0.245
C3	20	21.83	4.305		

Table 7 shows a comparison of *R.* apiculata heights after 12 weeks in Samples C1-C3, classified by proportion. There was no statistically significant difference at the 0.05 level (p > 0.05).

*Table 8. A comparison of the heights of R.*apiculate *at 12 weeks using the best proportion of each type of potting soil*

Sample	N	Mean	S.D.	F	P
A2	20	22.88[a]	4.292	19.819	0.000*
B1	20	17.95[b]	5.299		
C1	20	24.17[a]	5.198		*p≤0.05
D	20	10.42[c]	8.240		

Table 8 presents comparison of *R.* apiculata height at 12 weeks based on the best proportion of each type of potting soil. There was a statistically significant difference at the 0.05 level (p< 0.05). The planting soil and C1 ratio were the highest (24.17 cm), followed by A2 (22.88 cm), B1 (17.95 cm), and D (10.42 cm). From the pair test, according to the results of the pair test, there were five different pairs: A2 and B1, A2 and D, C1 and B1, C1 with D, and B1 with D.

3.5. Leaf Count

Table 9 shows a comparison of leaf amount induced by various planting soil nutrients after 12 weeks in samples A1-A3, classified by proportion. There is no statistically significant difference at the 0.05 level (p > 0.05).

Table 9. A comparison of leaf amount after 12 weeks in samples A1-A3

Sample	N	Mean	S.D.	F	P
A1	20	5.10	1.021		
A2	20	5.10	1.021	0.373	0.690
A3	20	5.33	0.966		

Table 10. A comparison of leaf amount after 12 weeks in samples B1-B3

Sample	N	Mean	S.D.	F	P
B1	20	4.20	1.105		
B2	20	3.90	1.210	40.397	0.000* *p≤0.05
B3	20	1.24	1.179		

Table 10 shows a comparison of leaf counts of *R.* apiculata at 12 weeks of sample B1 - B3 classified by proportion. There was a statistically significant difference at the 0.05 level (p≤0.05). The B1 ratio had the highest number of leaves (4.20 leaves), followed by B2 (3.90 leaves) and B3 (1.24 leaves), respectively. From the pair test, it was found that there were 2 different pairs, namely B1 and B3 and B2 and B3.

Table 11. A comparison of leaf amount after 12 weeks in samples C1-C3

Sample	N	Mean	S.D.	F	P
C1	20	5.60	0.828		
C2	20	5.10	1.021	1.441	0.246
C3	20	5.10	1.021		

Table 11 shows a comparison of leaf amount after 12 weeks in samples C1-C3, classified by proportion. There was no statistically significant difference at the 0.05 level ($p > 0.05$).

Table 12. A comparison of the leaf number of mangroves at 12 weeks using the best proportion of each type of potting soil

Sample	N	Mean	S.D.	F	P
A3	20	5.33^a	0.966		
B1	20	4.20^b	1.105	21.961	0.000* *p≤0.05
C1	20	5.60^a	0.828		

It was found that the number of leaves of mangroves at 12 weeks was compared with the best proportion of each type of potting soil. There was a statistically significant difference at the 0.05 level ($p \leq 0.05$). Sample C1 had the highest number of leaves (5.60 leaves), followed by A3 (5.33 leaves), and B1 (4.20 leaves), and D (2.63 cards), respectively. From the pair test, it was found that there were 5 different pairs, namely A3 with B1, A3 with D, C1 with B1, C1 with D, and B1 and D.

4. Conclusion

This study explores the utilization of Rubber Wood Fly Ash (RWFA) as a soil amendment for enhancing the soil quality in shrimp farms while investigating the effects of RWFA on the growth of R. apiculata Blume. The investigation reveals that RWFA, a byproduct of burning rubber wood for energy, has substantial potential to augment soil nutrient properties, acting as both a fertilizer and a liming agent, albeit with half the efficacy of commercial lime in the latter role. Significant alterations were observed in soil characteristics with the application of RWFA; the pH saw a substantial increase from 8.35 in the control to between 10 and 13 in the treated samples, signifying its role in neutralizing soil acidity. It also enhanced the soil's available phosphorous, extractable potassium, sodium, and chloride concentrations, demonstrating its prowess as a nutrient supplement.

The incorporation of RWFA in soil revealed a favorable correlation with mangrove growth rates, indicating its beneficial properties in fostering the development of R. apiculata seedlings. The mangroves exhibited optimal growth, with heights reaching between 15 to 25 cm initially. However, the assessment and application of RWFA require meticulous consideration due to the high concentrations of varied elements it contains, impacting the solubility of different nutrients and potentially posing risks to soil quality and biota. The experimental sets demonstrated divergent growth patterns and soil pH levels dependent on the ash type and addition ratio, underscoring the importance of precise application to maximize growth and yield. Specifically, experimental set C1 (soil: ash, 3:1) yielded the highest growth compared to sets A2 (soil: ash, 2:1) and B1 (soil: ash, 3:1). In conclusion, while RWFA emerges as a promising, sustainable soil amendment solution, offering substantial benefits in nutrient supplementation and soil acidity neutralization, its application necessitates rigorous assessment and management to mitigate potential adverse impacts on the environment. This research provides a foundational understanding and framework for leveraging biomass waste, paving the way for further explorations into sustainable agricultural practices and effective waste management strategies.

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