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Feasibility study of coconut shell biochar production using community-scale biochar kiln

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Abstract

The enormous coconut shell waste from local farmers and manufacturers has caused negative environmental and economic impacts in Thailand. A low-cost, small-scale pyrolysis kiln comprised of a cylindrical tank, gas circulating pipes, a kiln stand, and a manual drum lever was constructed and used to produce biochar from coconut shells in this study. The air intake and holding times for the biochar production process were varied. The biochar yield was 30.67% to 36.22%, or 4.6 kg to 5.4 kg per day per unit. The biochar porosity and fixed carbon content increased as the air intake and holding times were increased. The BET surface areas were 7.54 $m^2 \cdot g^{-1}$ to 63.17 $m^2 \cdot g^{-1}$. The pH values of biochar were alkaline, in the range of 7.34 to 10.24. Therefore, biochar can be used as a soil amendment material. The Net Present Value (NPV), the Internal Rate of Return (IRR), and the payback period are 52,757 THB (1,459.79 USD), 18.71%, 4 years, 10 months, and 27 days, respectively. According to economic analysis, investing in coconut shell biochar production under optimal conditions using the developed kiln is acceptable and can be viewed as a potential approach to providing additional economic benefits for coconut-based enterprises and the Thai community.

1. Introduction

Around 62 million metric tons of coconuts were produced annually worldwide, and 75% of the production was from Asian countries, including Thailand [1]. According to the Office of Agricultural Economics, in 2020, more than 618,000 metric tons of coconuts were produced on approximately 138,000 hectares of agricultural land in Thailand, mainly in Prachuap Khiri Khan Province [2]. In this area, a number of coconuts are generally grown and harvested by small-scale farmers and then processed into coconut products, e.g., coconut water, coconut oil, and coconut milk, by local manufacturers. Increases in coconut demand also lead to a large amount of coconut waste in agricultural and production processes. This enormous waste has caused difficulty for local farmers and manufacturers to process, reuse, and manage these wastes appropriately, further creating negative environmental and economic impacts [3-6]. Therefore, there is a need for sustainable waste management in a zero-waste community.

Approximately 15% of the entire coconut fruit can be wasted as coconut shell, which results in a significant volume of coconut shell being produced each year by coconut manufacturers [7]. Coconut shell waste is one of the most readily available, affordable, naturally abundant, and renewable resources [5,8]. The conversion of coconut shells into biochar is an environmentally beneficial method that promotes sustainable waste management and valorization. Biochar is well-known as bio-charcoal produced by pyrolysis of organic biomass in the absence of oxygen or under low oxygen conditions [9-11]. Slow pyrolysis conducted at low temperatures (300°C to 550°C) and for a prolonged time (>60 min) can be used efficiently to convert agriculture wastes to high yields of biochar and low yields of bio-oil and gaseous by-products [12,13]. Biochar has a positive impact on environmental sustainability because of its alkalinity and high porosity and can be used as a soil amendment to improve soil fertility and plant productivity, as well as a filter media to reduce wastewater and air pollution [14-16]. The biochar production process provides less air pollution than the conventional process of charcoal production and the open-air burning of agricultural residues, which emit toxic substances, greenhouse gases, and smoke particles, causing air pollution and public health effects [17]. The quality and characteristics of biochar vary greatly depending on the type of feedstock material, production technology, and type of reactor [18]. However, the biochar kiln with advanced technology is excessively expensive and unaffordable for small farmers and local coconut-based enterprises to produce a sufficient quantity of high-quality biochar for themselves.

Consequently, a low-cost, small-scale biochar kiln that was simple to build and use for producing coconut shell biochar locally was developed in this work, thereby benefiting small farmers and enterprises. To reduce smoke emissions and provide a more economical fuel utilization, the idea of using pyrolysis gasses as external gaseous fuels was also incorporated into the design of the biochar kiln. The biochar kiln unit was equipped with a kiln stand and a manual drum lever that can save time when collecting the biochar. The biochar production process was carried out with varying air intake times and holding times. Then, the yield and characteristics of the resulting biochar were investigated. The Taguchi method combined with Grey relational analysis was used to perform multiple response optimization of the biochar production condition. Moreover, the preliminary economic feasibility study of coconut shell-based biochar production with a fabricated kiln was estimated to demonstrate its economic benefits.

2. Experimental

2.1 Design and construction of community-scale biochar kiln

In this work, the biochar kiln prototype was designed for coconut-based enterprises and communities. The 3D model of the biochar kiln prototype was created in Autodesk Inventor 2020 software, as illustrated in Figure 1. The prototype is made up of a 550 mm-diameter by 800 mm-height tubular tank that is supported by a stand and has a manual drum lever. The main body panel was made from double layers of SS400 mild steel sheets, where the clay mixed with rice husk ash used as an inexpensive insulator was fabricated. In the middle of the pyrolysis chamber was a 180 mm-diameter combustion chamber with a fireplace. The 73-liter pyrolysis chamber is designed as a hollow cylindrical tank with inner and outer diameters of 180 mm and 450 mm and a height of 550 mm. It is connected to carbon steel pipes so that non-condensable gasses can circulate into the space between the pyrolysis chamber and the main body panel. Then, the gasses could enter the combustion chamber to be used as external gaseous fuels, thereby providing a more economical fuel and reducing smoke release. The bottom end of each circulating pipe has a hole for tar collection. The steel lid and chimney with air intake holes were placed on top of the biochar kiln. The assembled kiln is shown in Figure 2(a).

2.2 Biochar production using community-scale biochar kiln

The biochar production was carried out with the developed kiln in accordance with Taguchi's experimental design, which is shown in Table 1. The waste coconut shells used as raw biomass in this work were collected from a small-scale industry located in the southern part of Prachuap Khiri Khan Province, Thailand. After removing the fibers and husks, the coconut shells were dried in the sunlight for several days and then crushed into small pieces. The 15 kg of coconut shells and the around 5 kg of dried rubber wood branches were loaded into the pyrolysis chamber and the fuel combustion chamber, respectively. The pyrolysis chamber was first covered with a hollow steel lid, which allowed the pyrolysis reaction to take place without oxygen entering the chamber. Then, the steel lid of the biochar kiln was closed and fastened with four wing screws. On the steel lid, a chimney with air inlet holes was installed. The ignition was carried out in the fireplace while maintaining air intake. The slightly released smoke from wood combustion was observed from the chimney for approximately 15 minutes during start-up, and was most likely caused by moisture in wood fuels. After that, the fire was clear without smoke, as shown in Figure 2(b). The generated heat in the fuel combustion chamber could evenly transfer into coconut shells in the pyrolysis chamber. The fuel combustion process was carried out with varying air intake times (40, 60, and 80 min). Then, the top, holes in the chimneys, and fireplace were closed to block the air intake. Lastly, the biochar was removed and weighed after the slow pyrolysis process was done at three different holding times (4, 6, and 8 h). Coconut shell samples were slowly pyrolyzed in the pyrolysis chamber at temperatures ranging from 305°C to 375°C under various pyrolysis conditions. The photograph of a biochar sample produced in this study is shown in Figure 2(c).

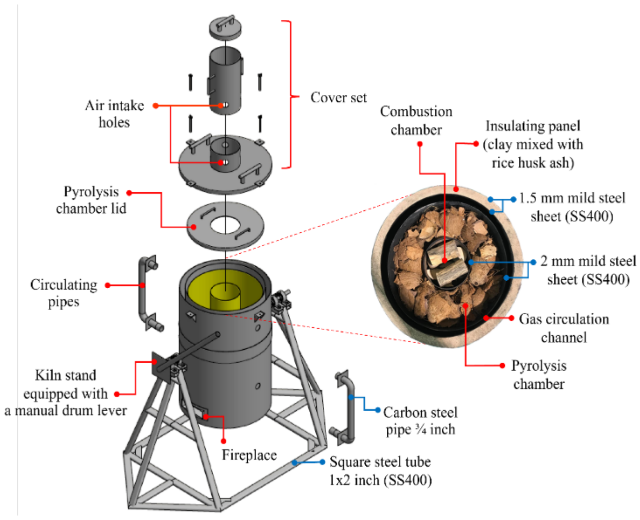


Figure 1. The 3D model of a community-scale biochar kiln prototype.

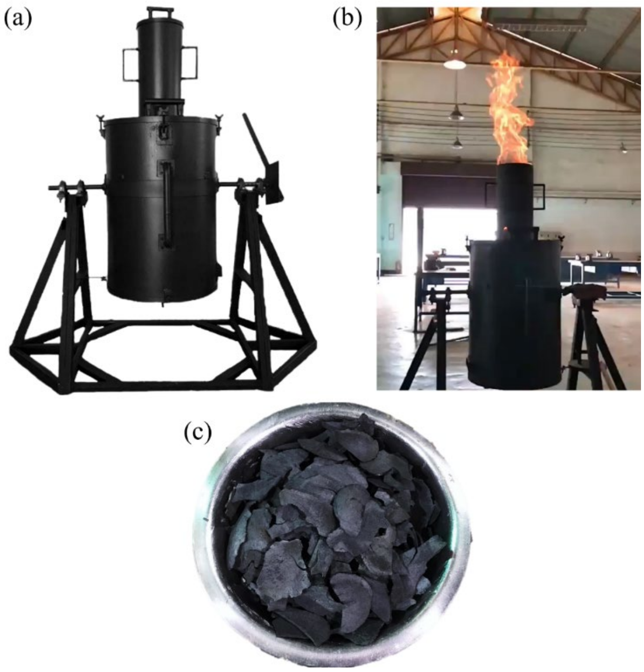


Figure 2. (a) The community-scale biochar kiln developed in this work, (b) the biochar production from coconut shells, and (c) the photograph of a produced biochar sample.

2.3 Biochar characterization

The yield of biochar produced by the pyrolysis of coconut shells in the designed kiln was calculated using Equation (1).

Table 1. Taguchi's experimental design of biochar production using developed kiln.

Run No.	Sample	A: Air intake time (min)	B: Holding time (h)
1	40-4	40	4
2	40-6	40	6
3	40-8	40	8
4	60-4	60	4
5	60-6	60	6
6	60-8	60	8
7	80-4	80	4
8	80-6	80	6
9	80-8	80	8

$$\text{yield}(\%) = (W_b / W_r) \times 100 \tag{1}$$

where W_b is the weight of biochar (kg) and W_r is the initial weight of raw biomass (kg). To determine the average, three replicates of each experiment were used.

The proximate analysis was performed to determine the moisture content, volatile matter, and ash content of raw biomass and derived biochar according to ASTM D3173, ASTM D3175–77, and ASTM D3174, respectively. The fixed carbon content was determined by subtracting the total of moisture, ash, and volatile matter from 100.

The surface morphology of biochar was observed by a scanning electron microscope (SEM, JEOL JSM-6510LV). The samples were coated with a thin layer of gold-palladium using the quorum sputter coater before SEM measurement.

The surface area of biochar was examined with a surface area and porosity analyzer (Micromeritics ASAP 2460) using N_2-adsorption-based techniques (Brunauer–Emmett–Teller, BET surface area). The reported values are the average of three replicates.

The pH of the biochar solution was analyzed by placing the five grams of ground sample in 50 mL of deionized water. The mixture was then stirred at room temperature for 30 min. After the filtration process, the pH of the aqueous solution was measured using a pH meter. Three replicates were used to calculate the means.

2.4 Taguchi method combined with Grey relational analysis

The production of coconut shell biochar was optimized for multiple responses, including yield, surface area, and pH, using Taguchi's experimental design with two factors and three levels that included air intake time (factor A = 40, 60, and 80 min) and holding time (factor B = 4, 6, and 8 h). Table 1 presents the results of a total of nine experiments using the Taguchi method with the L9 (3^2) orthogonal arrays.

For single-response optimization, the signal-to-noise (S/N) ratio was used to evaluate each factor's impact on response. The yield, surface area, and pH value responses were expected to be maximized. The S/N ratio was therefore examined using the "larger-the-better" performance characteristic, as expressed in Equation (2).

$$\text{(S/N)} = -10\log\left[1/R \sum_{f=1}^{R} 1/y_i^2\right] \tag{2}$$

where R is the number of all data points and y_i is the value of i^{th} data point.

The two-way analysis of variance (ANOVA) was employed to determine the P values and percentage contributions at the 95% confidence level ($P < 0.05$) without replication in order to identify the significant variables and quantify their effects on the response characteristics.

Multiple response optimization can be converted to single response optimization using grey relational analysis. The highest total Grey relational grade, which denotes the best formulation, can be evaluated using the S/N ratios of all responses acquired using the Taguchi approach. Data normalization is initially necessary. The quality characteristic of the "larger-the-better" is described in Equation (3).

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \tag{3}$$

where $x_i(k)$ is the value after Grey relational generation, $\min y_i(k)$ is the smallest value of $y_i(k)$ for k^{th} response, and $\max y_i(k)$ is the largest value of $y_i(k)$ for k^{th} response.

The Grey relational coefficient can then be calculated via the following Equation:

$$\gamma\left(x_0^*(k), x_i^*(k)\right) = \frac{\Delta_{\min} + \zeta\Delta_{\max}}{\Delta_{0i}(k) + \zeta\Delta_{\max}} \tag{4}$$

$$0 < \gamma\left(x_0^*(k), x_j^*(k)\right) \le 1$$

where $\Delta_{0i}(k) = \left|x_0^*(k) - x_i^*(k)\right|$,

$$\Delta_{\max} = \underset{\forall j \in i}{\max}\,.\,\underset{\forall k}{\max}\,.\left|x_0^*(k) - x_j^*(k)\right|$$

$$\Delta_{\min} = \underset{\forall j \in i}{\min}\,.\,\underset{\forall k}{\min}\,.\left|x_0^*(k) - x_j^*(k)\right|,$$

ζ is the distinguishing coefficient, $\zeta \in [0,1]$.

If all variables are weighted equally, the value of ζ is usually set to 0.5. The Grey relational grade can then be calculated using Equation (5).

$$\gamma\left(x_0^*, x_i^*\right) = \frac{1}{n}\sum_{k=1}^{n} \beta_k \gamma\left(x_0^*(k), x_i^*(k)\right) \tag{5}$$

Finally, the maximum Grey relational grade of each parameter can be used to determine the best parameters for producing coconut shell biochar.

2.5 Economic feasibility analysis

A preliminary economic analysis of coconut shell-based biochar production was conducted, and the scope of the analysis is for small and medium enterprises (SMEs) located in the southern part of Prachuap Khiri Khan province. In the first step of the study, the enterprise budget cost, including the fixed costs, variable costs, and miscellaneous, was determined. The fixed costs, including the cost of equipment and machines for kiln construction, biochar production processes, and packaging units, were calculated. The variable costs, which consist of the raw materials, labor, utility, equipment maintenance and repair, biochar packaging, waste disposal, and factory overhead, were determined. The ten-year estimated annual cash flow at the discount rate of 10% is conducted for one profitable cycle for a biochar production enterprise.

Generally, Net Present Value (NPV) based on an MS Excel spreadsheet is examined as follows:

$$\text{NPV} = -CF_0 + \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} \tag{6}$$

where CF_0 is the total initial investment costs; CF_t is the cash flow expected to be received in each period; r is the discount rate; n is the number of periods during an investment that is expected to operate and generate cash inflows. A positive NPV indicates that an investment should be accepted, whereas a negative NPV shows that the investment is inefficient and should be rejected.

Internal Rate of Return (IRR) can be expressed as follows:

$$0 = \sum_{t=0}^{n} \frac{CF_t}{(1+IRR)^t} \tag{7}$$

where CF_t is the cash flow expected to be received in each period; n is the number of project years. If the IRR is higher than the discount rate, the proposed project is economic feasibility.

The payback period is the time required to recover the funds expended on an investment. The payback period is usually measured at a break-even point in time when the cumulative positive cash flow is equal to the negative cash flow. An investment with a shorter payback period is typically more economically favorable than one with a longer payback period. Thus, shorter payback periods mean more profitable investments and more desirable results.

3. Results and discussion

3.1 Biochar yield

After the biochar production study, agro-waste coconut shells could be carbonized into biochar using the kiln developed in this work. The produced biochar was weighted after the cooling process, and the yield was then calculated as shown in Figure 3. Considering only the production yield of biochar, the values were in the range of 30.67% to 36.22% on a dry-weight basis. It appears that the biochar yield decreased slightly when the air intake time increased from 40 min to 60 min. It is typically accepted that the increasing time of air intake commonly refers to oxygen enrichment. When more air was supplied to the combustion chamber, the exothermic combustion reactions of the fuel wood were accelerated, leading to the rapid flame propagation and heat release rate during the experiment [19,20]. The high heat release could transfer to the pyrolysis chamber through convection, and hence the temperature in the pyrolysis chamber might increase slightly, resulting in less biochar yield. This was probably because of the more complete decomposition of hemicellulose and cellulose components and the increased devolatilization of organic materials with increased pyrolysis temperatures [21,22]. It was also observed that the holding time had a significant influence on the biochar yield. The biochar yield declined with increasing holding time, mainly because of the ongoing pyrolysis reaction. It is consistent with a previous study conducted by Yu *et al.*, who found that the yield of biochar derived from pruned wolfberry branches decreased as the holding time increased because the longer holding time could lead to a more complete pyrolysis reaction [23]. Yang *et al.* [24] also reported a similar result, in which the yield of biochar derived from pruned apple tree branches decreased from 32.84% to 31.61% when the holding time increased from 1 h to 6 h.

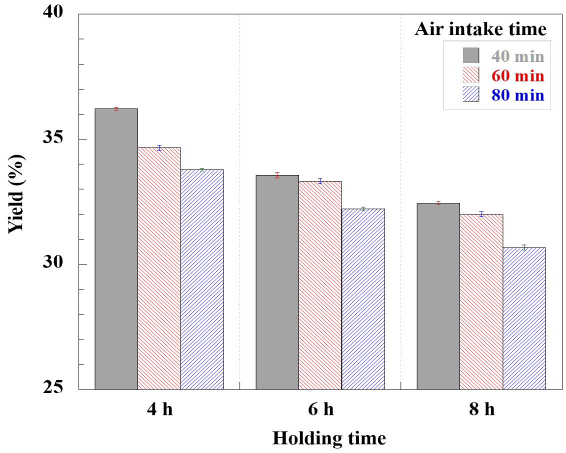
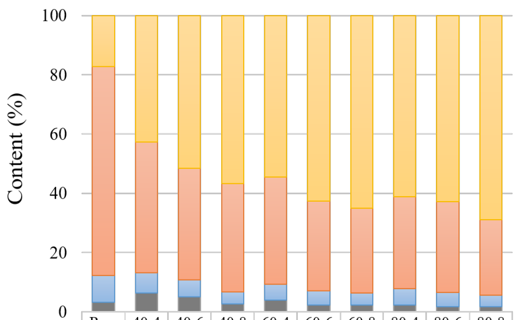


Figure 3. The production yield of biochar derived from coconut shells using community-scale biochar kiln.



	Raw	40-4	40-6	40-8	60-4	60-6	60-8	80-4	80-6	80-8
Fixed Carbon (%)	17.23	42.74	51.55	56.80	54.56	62.73	65.08	61.21	62.81	69.01
Volatites (%)	70.46	44.17	37.67	36.50	36.17	30.17	28.67	31.00	30.67	25.33
Moisture (%)	9.08	6.76	5.78	4.03	5.27	4.77	4.00	5.46	4.85	3.99
Ash (%)	3.23	6.33	5.00	2.67	4.00	2.33	2.25	2.33	1.67	1.67

Figure 4. Proximate analysis of the coconut-shell raw biomass and biochar produced at different pyrolysis conditions.

3.2 Proximate analysis

The component content of raw coconut shells was determined using the proximate analysis before the experiment. As shown in Figure 4, the results were quite similar to those reported in the literature [8,25,26] for the fixed carbon, ash, volatile matter, and moisture content of coconut shells, which were 8.08, 3.23, 70.46, and 18.23, respectively. After pyrolysis, all samples were obtained with less than 7% ash. A slight decrease in ash content was observed with longer air intake times and holding times. This could be because some inorganic compounds volatilize into gases or liquids at higher pyrolysis temperatures over longer periods of time [27]. This finding is consistent with a previous study by Suman *et al.*, who discovered that as temperature increased, the ash content of coconut husk biochar decreased [28]. Furthermore, Palniandy *et al.* [29] found that the ash content of rubber wood biochar decreased with increasing temperature, possibly as a result of some inorganic materials vaporizing into gas or liquid. The percentage of volatile matter and moisture content of the biochar significantly decreased with longer air intake and holding times, while the amount of fixed carbon increased. It was mainly due to dehydration and devolatilization reactions [30,31]. This result also suggested that more volatiles were lost with increasing air intake and holding times due to the higher temperature and longer pyrolysis reaction time. This phenomenon is similar to that explored in the study by James *et al.* [32], in which the volatile matter of wood chip biochar decreased from 31.8% to 6.6% when the airflow increased. It is typically associated with the release of more volatiles as a result of an increase in reaction temperature and rising airflow in a top-lit updraft gasifier.

3.3 Morphological observation

Figure 5 shows the SEM images at 1000x magnification of the morphology of the coconut shell biochar obtained under different pyrolysis conditions. It was observed that the biochar produced at 40 min of air intake within 4 h of holding time had numerous hollow channels with a dense surface and few pores, as depicted in Figure 5(a). Increasing the air intake duration and holding time produced biochar with increased porosity and a variety of pore shapes, as illustrated in Figure 5(b-i). This means that the coconut shell had more time to react with the air, resulting in the radical development of more pore structures due to the release of a large amount of volatiles [33]. This result was in agreement with the findings of the approximate analysis. The pore structures were inherently heterogeneous and structurally complex, with a multiscale elongated shape. This was also observed by Batista *et al.*, who found that the biochar derived from various waste biomasses, including coconut shells, revealed a very complex structure of pores and channels with different sizes after pyrolysis under a controlled atmosphere in a tunnel oven [34]. As can be seen from Table 2, the BET surface areas of the resulting biochar were in the range of 7.54 $m^2 \cdot g^{-1}$ to 63.17 $m^2 \cdot g^{-1}$. The highest BET surface area was found in the biochar that was produced with an air intake time of 80 min and a holding time of 6 h. The BET surface area gradually increased as the holding time was increased from 4 h to 6 h. High porosity on the biochar surface was created as a result of the significant loss of volatile matter in the biomass [35,36]. Then, the decline in surface area was found when the holding time increased further. This was probably because of an over-development of the pore structures [33]. Another reason for this phenomenon was related to the reduction of adsorption sites due to the clogging of pores caused by the condensation of pyrolysis volatiles [17]. However, the BET surface area of biochar obtained in this work was still in the same range as those of previous studies. According to the results of Castilla-Caballero *et al.* [37], the BET surface area values of biochar derived from coconut shells obtained from the Colombian Pacific Coast were in the range of 9.85 $m^2 \cdot g^{-1}$ to 15.75 $m^2 \cdot g^{-1}$ after varying pyrolysis temperature and oxygen-feeding content in the pyrolysis reaction. Babatabar *et al.* [35] found that after pyrolyzing lignocellulosic and algal biomasses in a fixed-bed reactor, the BET surface area of coconut shell-derived biochar was 26.22 $m^2 \cdot g^{-1}$. Khuenkaeo *et al.* [38] also reported a BET surface area of 55.69 $m^2 \cdot g^{-1}$ for biochar produced from coconut shells collected from local farms in northern Thailand using a rotating blade ablative reactor. When used as a soil conditioner, biochar with a large surface area and high porosity can improve soil aeration, water-holding capacity, and water infiltration from the ground to the topsoil after a heavy rain by increasing the total porosity of the soil [39]. It can also be utilized as a nutrient carrier to enhance nutrient retention, microbial habitation, fertilizer effectiveness, and plant productivity [15,21]. Consequently, it can be added to the soil as a long-term amendment to manage soil health.

3.4 pH

In Table 2, the pH values of the resulting biochar ranged between 7.34 and 10.24. It is clearly observed that the biochar tended to be highly alkaline with the increase in air intake time and holding time. This was possible because the longer pyrolysis reaction time and higher pyrolysis temperature, induced by longer air intake time, could encourage the formation of basic surface oxides, which were produced by the thermal decomposition of organic materials, as well as the disappearance of acidic functional groups like –COOH and –OH [31,40]. It is similar to Pituya *et al.*'s study, which explored the properties of biochar produced from Acacia wood and coconut shell by varying pyrolysis temperatures (300°C to 500°C) and time (1 h to 3 h). The pH of Acacia wood-derived biochar ranged from weak acidic to weak basic (pH 5.5 to 7.9), while coconut shell-derived biochar trended to be more basic (pH 6.4 to 9.3) [41]. According to the studies by Wang *et al.*, the pH of swine-manure-derived biochar tended to increase with increasing pyrolysis temperature and holding time. The maximum values of pH were in the range of 9.9 to 12.9 when the pyrolysis reaction was done at a temperature ranging from 300°C to 750°C [22]. Khawkomol *et al.* [17] also reported that the pH value of coconut shell-derived biochar produced in a horizontal drum kiln was 9.02. Biochar has the potential to indirectly affect nutrient availability by altering soil pH. Biochar can be added to acidic soil to raise the pH because of its alkalinity, which makes it useful as a liming agent [42]. A higher soil pH increases nutrient availability and decreases the percentage of Al^{+3} and H^+ ions occupying cation exchange sites on the soil particle surface, resulting in increased base saturation [43].

Table 2. BET surface area and pH of biochar produced at different pyrolysis conditions.

Sample	BET Surface Area (m²/g)	pH
40-4	7.54 ± 0.31	7.34 ± 0.08
40-6	14.18 ± 0.12	7.47 ± 0.20
40-8	24.82 ± 0.16	9.37 ± 0.16
60-4	17.55 ± 0.04	8.77 ± 0.08
60-6	25.07 ± 0.84	9.68 ± 0.08
60-8	22.42 ± 0.65	9.97 ± 0.01
80-4	37.96 ± 1.30	8.85 ± 0.08
80-6	63.17 ± 2.27	9.46 ± 0.13
80-8	39.50 ± 1.31	10.24 ± 0.00

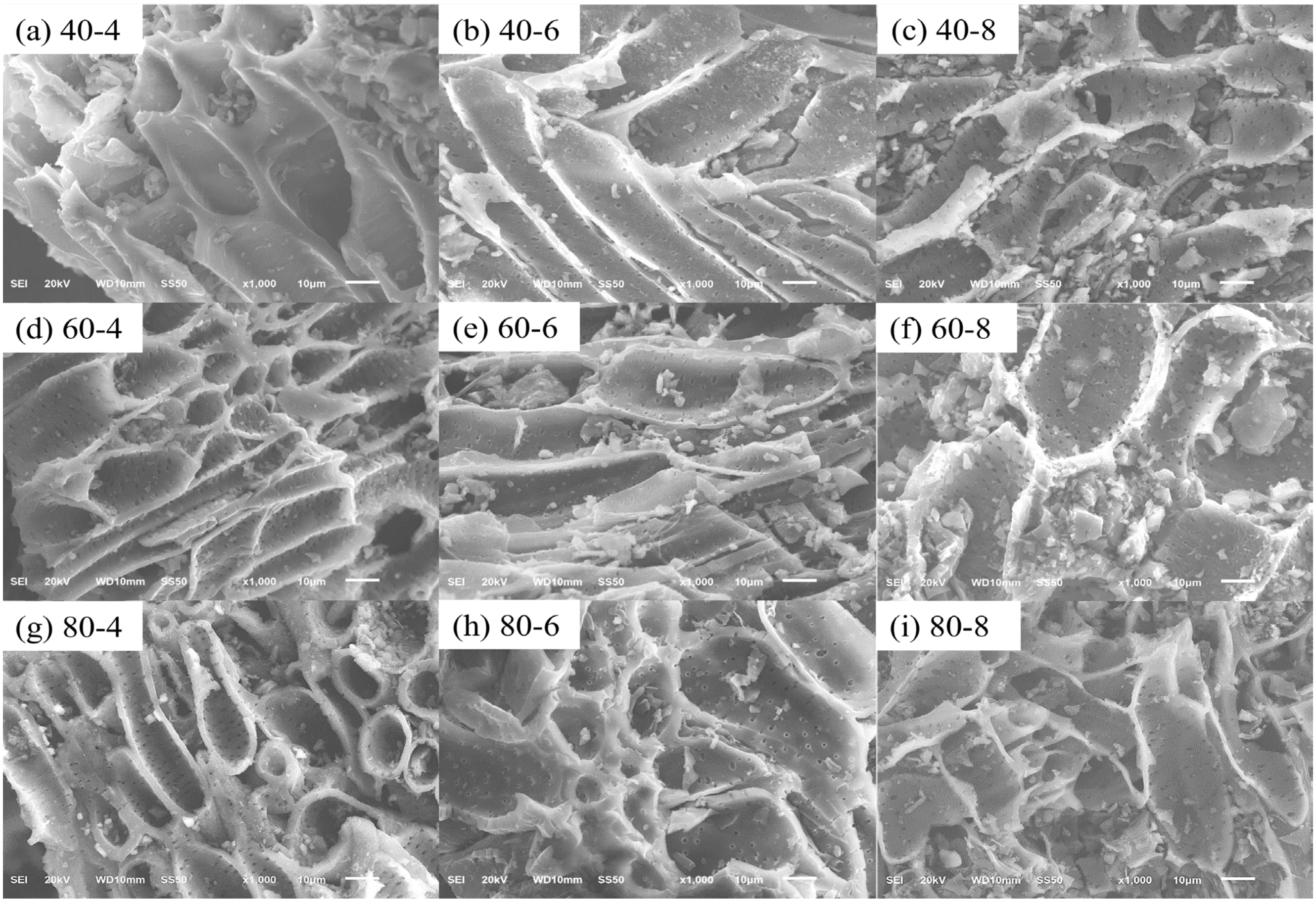


Figure 5. Structure morphological images at 1000x magnification of the coconut shell biochar analyzed SEM.

3.5 Multiple response optimization of the coconut shell biochar production parameter

Figure 6 depicts the main effect plots for the mean values and S/N ratio of each individual response level in order to investigate the effects of each parameter on the yield, surface area, and pH values of coconut shell biochar. Additionally, the significance of the variables and how they affected the response characteristics were examined using the two-way ANOVA at the 95% confidence level ($P < 0.05$). The results are shown in Table 3. The mean yield of the samples was in the range of 32% to 34%, as shown in Figure 6(a). Lower S/N ratio values were observed as air intake and holding times increased. The optimal conditions for yield were found at A_1B_1 with 40 min of air intake time (1st level of factor A) and 4 h of holding time (1st level of factor B). Based on the ANOVA analysis, air intake and holding times both had a significant impact on yield, with a low P value ($P < 0.05$) and contribution values of 24.61% and 72.69%, respectively. In the case of BET surface area, a larger response is preferable because a higher S/N ratio indicates a larger surface area. As shown in Figure 6(b), the S/N ratio increased with increasing air intake time, whereas increasing holding time to 8 h tended to decrease the S/N ratio. The average BET surface area values ranged from 15.51 $m^2 \cdot g^{-1}$ to 46.88 $m^2 \cdot g^{-1}$. Air intake time exhibited the most significant effect on the surface area of biochar, with a low P value ($P < 0.05$) and a contribution value of 74.05%. The best conditions for producing biochar with the greatest surface area were found at A_3B_2 with 80 min of air intake time (3rd level of factor A) and 6 h of holding time (2nd level of factor B). The main effect plots for biochar pH mean values and S/N ratios are shown in Figure 6(c). The mean values of biochar pH ranged from 8.06 to 9.52. The longer air intake and holding times resulted in higher S/N ratios, which suggested that the biochar tended to be highly alkaline. The highest pH value was observed at A_3B_3 with 80 min of air intake time (3rd level of factor A) and 8 h of holding time (3rd level of factor B). Both air intake and holding times had low P values (P0.05), indicating that they had a significant influence on pH. The percentage contributions of air intake and holding times were 48.72% and 43.20%, respectively. The relationship between the factors and the responses of the coconut shell biochar could be predicted as follows:

$$\text{yield}(\%) = 40.765 - 0.04625X_1 - 0.7967X_2 \quad (8)$$

$$\text{surface area } (\text{m}^2/\text{g}) = -30.9 + 0.784X_1 + 1.97X_2 \quad (9)$$

$$\text{pH} = 4.522 + 0.0364X_1 + 0.385X_2 \quad (10)$$

where X_1 is air intake time (min) and X_2 is holding time (h).

The Taguchi method and Grey relational analysis were coupled to solve multiple response optimization of the coconut shell biochar production parameter. Equation (3) was used to normalize the data for the "larger-the-better" quality characteristic. Equation (4-5) were then used to calculate the Grey relational coefficient and Grey relational grade. The Grey relational analysis results are shown in Table 4. Grey relational grade was typically used to determine the level of correlation among the sequences. The optimal factor level could be represented by the level with the highest Grey relational grade value. Based on the Grey relational grade tabulated in Table 5, the optimal condition for the production of coconut shell biochar was suggested as the A_3B_3 condition with 80 min of air intake time (3rd level of factor A) and 8 h of holding time (3rd level of factor B). Run number 9 yielded the properties of biochar under optimal production conditions. When the optimal conditions for biochar production were used, there was good agreement between the predicted and actual values of Grey relation grade.

3.6 Economic feasibility analysis

Preliminary economic analysis was done to estimate the cost of producing coconut shell biochar under optimal conditions determined by the Taguchi method combined with Grey relational analysis, which were 80 min of air intake time and 8 h of holding time using a community-scale biochar kiln. Table 6 presents the itemized cost estimation, including fixed cost, variable cost, and working capital. The total initial investment cost was 54,275 THB. Noted that the cost of land, building, raw material transportation, and utility system installation was not considered in the fixed cost since the biochar pyrolysis unit would be installed in the same location as waste coconut shell storage in coconut-based enterprises. The operating cost is estimated based on the average of 256 working days per year over ten years of the project's life. The labor cost for the biochar production

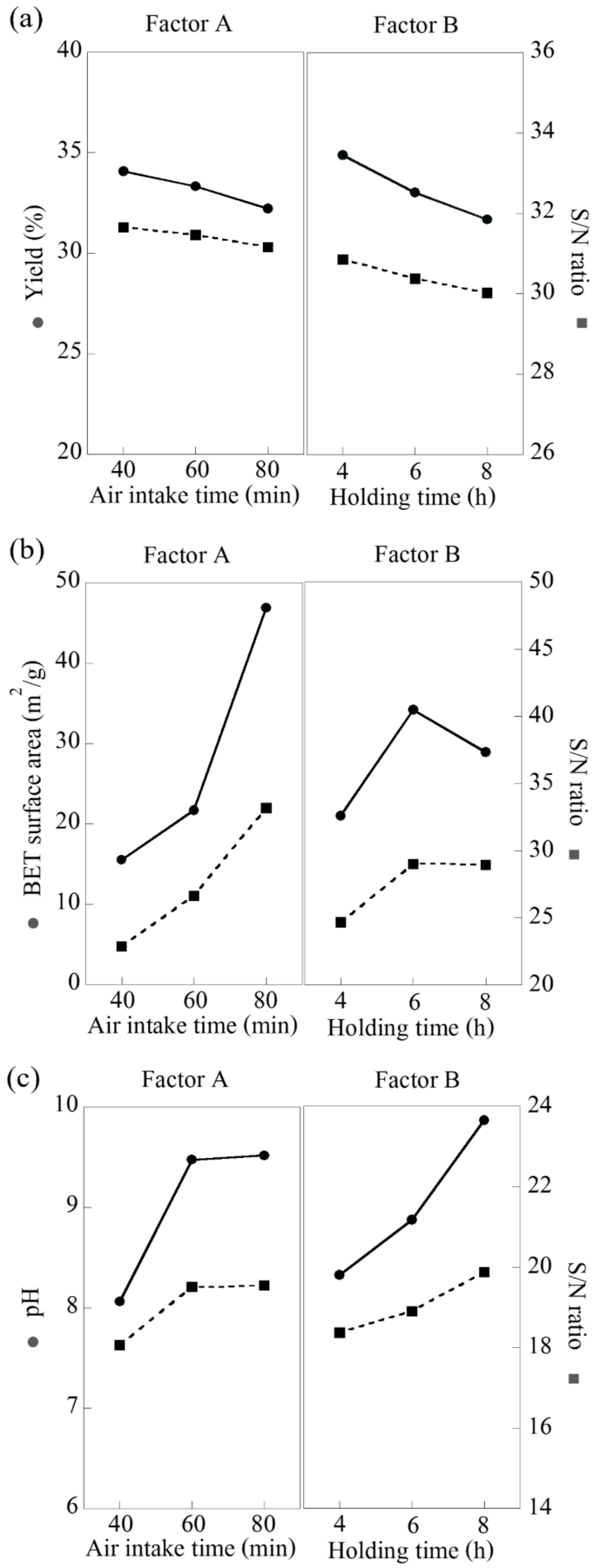


Figure 6. Effect of factors on (a) yield, (b) surface area, and (c) pH of the biochar samples.

plant was calculated using a one-person operation and a ten-hour workday. The total variable cost is 142,370 THB (3,939.41 USD) per year. The working capital of the first year is approximately 113,896 THB (3,151.52 USD). Two biochar pyrolysis units were employed in this work. These units had a production capacity of about 9.2 kg of biochar per day, or 2,355 kg annually, based on a year with 256 working days on average. The annual revenue was 176,640 THB (4,887.66 USD) and was expected to remain constant throughout the project's life. This was calculated by retailing the annual biochar production capacity of 2,355 kg at 75 THB (2.08 USD) per kg, which is averaged based on the three different commercial biochar retailers in Thailand. The profitability analysis of biochar production from coconut shells using a community-scale biochar kiln is summarized in Table 7. The NPV is 52,757 THB (1,459.79 USD), which is greater than zero, thus the project will be accepted. The payback period is shortened to 4 years, 10 months, and 27 days. The obtained IRR is 18.71%, which is higher than the discount rate (10%) as well. For the preliminary economic evaluation, the investment in this project is worth more than it costs and should be a worthwhile undertaking. According to Giwa *et al*. [44], the production of biochar from date palm waste using a concentrated solar energy-based tubular pyrolysis reactor was more economically feasible, with an IRR of 14.8% and a payback period of 4 years, 4 months, and 12 days based on the biochar price of approximately 99 THB (2.74 USD) per kg. As a result, producing biochar from waste coconut shells using a community-scale biochar kiln can be considered a competent approach to generating additional economic benefits for coconut-based enterprises.

Table 3. The analysis of variance (ANOVA) results for all responses.

Factor	Degree of freedom	Sum of squares	Mean square	F-Value	P-Value	Contribution
Yield						
Air intake time	2	5.2022	2.6011	18.17	0.010	24.61
Holding time	2	15.3675	7.6837	53.68	0.001	72.69
Error	4	0.5725	0.1431			2.71
Total	8	21.1422				100.00
Surface area						
Air intake time	2	1656.6	828.28	10.40	0.026	74.05
Holding time	2	261.9	130.95	1.64	0.301	11.71
Error	4	318.6	79.64			14.24
Total	8	2237.0				100.00
pH						
Air intake time	2	4.1213	2.0606	12.06	0.020	48.72
Holding time	2	3.6542	1.8271	10.70	0.025	43.20
Error	4	0.6833	0.1708			8.08
Total	8	8.4588				100.00

Table 4. The results of Grey relational analysis for nine comparability sequences.

Run No.	Grey relational coefficient			Grey relational grade
	Yield	Surface area	pH	
1	1.0000	0.3333	0.3333	0.5556
2	0.5102	0.3622	0.3436	0.4053
3	0.4237	0.4204	0.6250	0.4897
4	0.6410	0.3788	0.4966	0.5055
5	0.4902	0.4220	0.7214	0.5445
6	0.3968	0.4057	0.8430	0.5485
7	0.5319	0.5246	0.5106	0.5223
8	0.4098	1.0000	0.6502	0.6867
9	0.3333	0.5403	1.0000	0.6245

Table 5. The calculated Grey relational grades and results of confirmation experiment.

Level	Grey relation grade	
	A: Air intake time	B: Holding time
1	0.4835	0.5278
2	0.5328	0.5455
3	0.6112	**0.5542**
Delta	0.1276	0.0264
Rank	1	2
Grey relation grade of A_3B_3	**Predicted**	**Experiment**
	0.6229	0.6245

Table 6. Itemized cost estimation of coconut shell-derived biochar production using community-scale biochar kiln.

Type of cost	Annual quantity	Cost/unit (THB)	Cost (THB)
Fixed Cost			
Machines & Equipment			
- Shredder/Grinder (M2 TAZAWA 6.5HP)	1	32,000	32,000
- Pyrolysis Unit	2	6,500	13,000
- Electric Chainsaw (BERALA BL-8J113w 18V)	1	3,990	3,990
- Wheelbarrow (MARTON)	1	1,840	1,840
- Weighing Scale	1	680	680
- Stainless Steel Tray	1	765	765
Miscellaneous			2,000
Total Fixed Cost			54,275
Variable Cost			
Raw materials			
- Coconut shells	7,680 kg	2	15,360
- Rubber tree branch wastes	2,560 kg	0.70	1,792
Biochar packaging (zip-lock bag & label)	2,355 set	4	9,421
Manpower and personal	2,560 h	37.5	96,000
Utilities	256 unit	20	5,120
Maintenance & Repair			5,083
Waste Disposal			300
Factory Overhead			9,294
Total Variable Cost			142,370
Working Capital			113,896
1 USD = 36.14 THB			

Table 7. Estimated cash flows of coconut shell-derived biochar production using community-scale biochar kiln.

Year	Expenses (THB)	Revenues (THB)	Cash flow (THB)	Cumulative (THB)
0	54,275	0	-54,275	-54,275
1	256,266	176,640	-79,626	-133,901
2	142,370	176,640	34,270	-99,631
3	142,370	176,640	34,270	-65,361
4	142,370	176,640	34,270	-31,092
5	142,370	176,640	34,270	3,178
6	142,370	176,640	34,270	37,448
7	142,370	176,640	34,270	71,718
8	142,370	176,640	34,270	105,988
9	142,370	176,640	34,270	140,258
10	142,370	176,640	34,270	174,528

4. Conclusion

The small-scale biochar kiln was fabricated and used to produce coconut shell biochar for communities and small enterprises. The pyrolysis kiln prototype is a cylindrical tank equipped with a stand and a manual drum lever. The circulating pipes were connected with the pyrolysis chamber, where the non-condensable gases could flow into the gap between the pyrolysis chamber and the insulating panel and then enter the combustion chamber as external gaseous fuels, thereby reducing smoke pollution. Both air intake time and holding time had a significant effect on the production yield and the properties of the biochar. The biochar yield tended to decrease as the air intake time and the holding time increased. Due to pyrolytic volatilization during pyrolysis, the porosity and the fixed carbon content of biochar increased with longer air intake and holding times. The highest BET surface area of approximately 63.17 $m^2 \cdot g^{-1}$ was observed for the biochar produced at 80 min of air intake time and 6 h of holding time. The pH values of biochar were alkaline, in the range of 7.34 to 10.24, which could be considered a suitable material for soil amendment. The optimal conditions for making coconut shell biochar with a small-scale pyrolysis kiln were found at A_3B_3, with 80 min of air intake time (3rd level of factor A) and 8 h of holding time (3rd level of factor B), based on multiple response optimization using the Taguchi method along with Grey relational analysis. For the preliminary economic feasibility study results, the Net Present Value (NPV) is 52,757 THB (1,459.79 USD), the Internal Rate of Return (IRR) is 18.71%, and the payback period is 4 years, 10 months, and 27 days. As a result, investing in the production of coconut shell biochar using the developed pyrolysis kiln is economically feasible and can be viewed as a potential approach to generating additional economic benefits and achieving sustainable agro-waste management for coconut-based enterprises and communities.

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