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บทความวิจัย

Characteristics of Biochar Production Derived from Bamboo in a Drum Pyrolyzer

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Abstract: This study utilizes a drum pyrolyzer to investigate the production of biochar and wood vinegar from bamboo. Bamboo from Prachinburi province in Thailand was used in the experiment. Bamboo was heated to a temperature between 450 °C and 595 °C in a drum pyrolyzer (cylindrical shape). The yields of biochar, wood vinegar, and gaseous products following the pyrolysis process were at 34.6%, 16.6%, and 48.8%, respectively. Based on calculations using the yield of biochar and the heating values of both biochar and raw fuel, the pyrolyzer's energy conversion efficiency was at 44.6%. With moisture content dropping from 11.1% to 4.94%, volatile matter dropping from 78.0% to 39.2%, and fixed carbon rising from 19.8% to 52.4%, the resultant bamboo biochar displayed better properties than the raw material. Compared to the raw bamboo's 19.1 MJ/kg, the biochar's higher heating value (HHV) increased to 24.6 MJ/kg. During the pyrolysis process, the pH of the wood vinegar generated ranged from 2.85 to 3.18. Based on a one-year project timeline, the process showed economic potential with a monthly internal rate of return of 46.75% and a payback period of about two months.

Keywords: Bamboo; Biochar; Drum pyrolyzer; Pyrolysis

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1. Introduction

Thailand is the primary source of commercial bamboo, with 91,746 rai (14,679.4 hectares) of planted area distributed throughout all regions. With 40,364 rai (6,458.2 hectares) under cultivation, the Eastern region is the greatest area for bamboo farming [1]. The biggest area of Tong bamboo cultivation at the provincial level is found in Prachinburi province, which covered 31,061 rai (4,969.8 hectares) in 2018, according to figures on bamboo cultivation from the Prachinburi Provincial Agricultural Office [1]. This displays how bamboo can be used in Thailand as a raw material for sustainable energy.

Thailand's domestic coal (lignite) output is about 3,379 ktoe [2]. To further fulfill its energy requirements, Thailand imports coal 13,406 ktoe. In the final stages, the nation uses 8,413 ktoe as energy from coal [2]. Because of its rapid growth rate, bamboo is consequently seen as an attractive crop for alternative energy. This is considered to be a raw material that can be processed into biochar for use as renewable energy and that can sustainably replace coal use.

The street food business, which was valued at 180 billion baht in 2022 and grew at a rate of about 2-3% from the year previously, presents potential for the use of plant-based biochar [3]. Thus, plant-based biochar has the potential to be used in these businesses as a fuel for grilling and cooking.

One of the thermal chemical conversion processes that takes place in low- or no-oxygen environments is pyrolysis. This involves heating a material to the point when the molecules breakdown into smaller ones. The end products of the pyrolysis process, which uses biomass to create biochar, are the solids, liquids, and gases that are created. The principal gases that are often produced are carbon monoxide (CO), hydrogen (H_2), and methane (CH_4). According to Basu [4], these gases have high heating values of 12.63 MJ/Nm^3, 12.74 MJ/Nm^3 and 39.82 MJ/Nm^3 [4] respectively. These gasses can therefore be employed again as energy sources.

In addition to being an energy source, products from the pyrolysis process of agricultural waste have been investigated for use as materials for soil improvement and to improve agricultural production. The application of 10 t/ha of corn cob biochar as a soil amendment in cassava farms was investigated by Frimpong et al. [5]. The result revealed that cassava yields in the field with only biochar addition were 11.85 kg/ha, a 71% increase, whereas yields in the field without biochar and fertilizer were 6.91 kg/ha. More recently, Luan et al. [6] investigated the application of 0.5%, 2%, and 5% biochar ratios in soil for

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Chinese cabbage growth. According to the study, the dose of biochar given to Chinese cabbage plants increased their weight by 4.2% to 11.6% when compared to soil that lacked biochar. According to the abovementioned studies, biochar could improve agricultural yields and production and be a useful soil amendment.

The temperature of the reaction is an important factor that determines the amount and characteristics of biochar products that are produced by pyrolysis from biomass. According to the previous researches [7-9], temperatures typically used are between 300 °C and 750 °C. Kurimoto et al. [8] conducted a study on the production of biochar from bamboo in an electric furnace for three hours at temperatures between 300 °C and 800 °C. The study found that the amount of biochar produced, volatile matter content, hydrogen, and oxygen decreased with increasing temperature. The total carbon content, ash content, and fixed carbon content all increased at the same time.

This study is to investigate the method of making biochar from bamboo by utilizing a drum pyrolyzer that also produces wood vinegar in combination with a condensing unit. The study examines the qualities of the final products as well as the yield of solid and liquid products. Furthermore, this evaluates the process's financial viability by computing the payback period and taking into account potential applications for bamboo biochar, such as cooking and agricultural soil enhancement.

2. Apparatus and Experimental Procedure

2.1 Apparatus

This study examines the pyrolysis process used in a horizontal cylindrical reactor (also known as a drum pyrolyzer) to produce biochar from bamboo. The reactor is constructed from 5 mm thick steel sheet that has been rolled into a cylindrical shape with an internal diameter of 125 cm and a depth of 130 cm, as depicted in Fig. 1. A cooling tower is an additional component of the reactor that is used to contain the hot gas produced during the pyrolysis reaction. After cooling, the gas is recirculated to ignite and heat the reactor. Wood vinegar is the liquid that comes out of the condenser unit. Four steel pipes with a diameter of one inch each make up the internal cooling tower. Water cools the pipes at a steady 2.35 m^3/h flow. The reactor has two Type-K thermocouples installed: one is located inside the reaction chamber, while the other one measures the temperature of the cooled gas. The Testo 175-T3 data logger was used to record the temperatures every 10 seconds.

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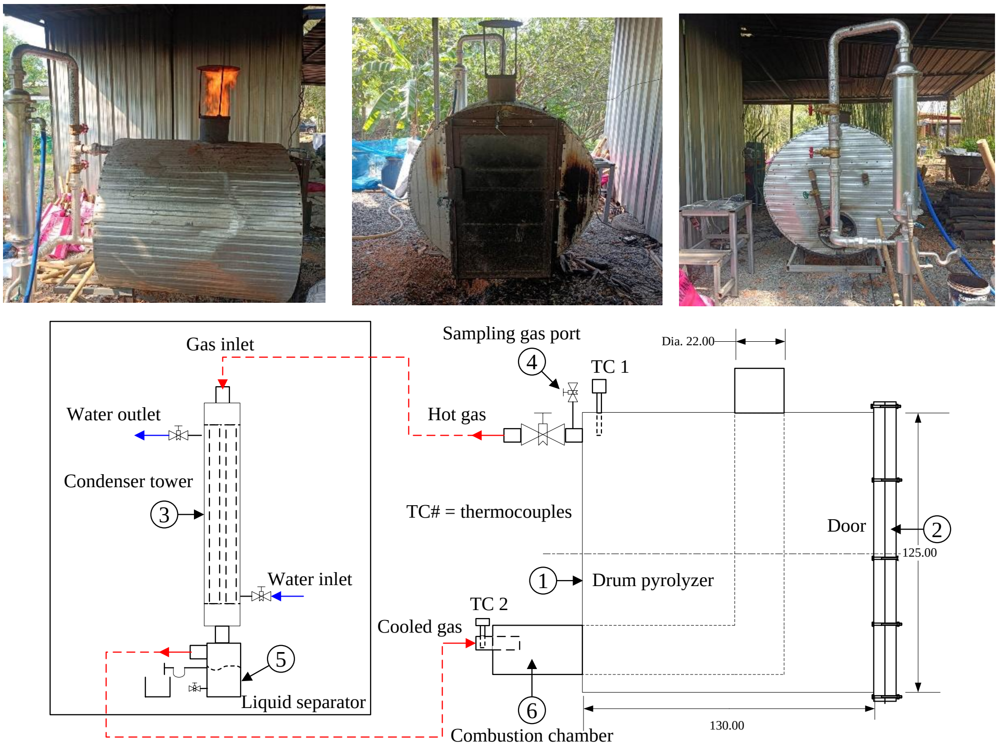

Fig. 1 Drum pyrolyzer and schematic diagram of the system

2.2 Experimental Procedure

In this study, the reactor was heated and pyrolysis processes were carried out using bamboo fuel. The bamboo (Thyrsostachys siamensis Gamble)utilized was grown in Prachinburi province and was around three years old.

Generally, the bamboo is 1-2 years old, its body is covered in sheaths; however, by the time it is 3 years old, these sheaths have decreased, making it simpler to cut and use for practical purposes.

The experiment started with the arrangement of bamboo pieces that were roughly 5 cm in diameter and 30 cm in length as shown in Fig. 2. Wood chips were used to start a fire in the reactor's fuel feed chamber at the bottom after it was fully loaded. After that, the reactor's temperature was raised by feeding it bamboo fuel. The pyrolysis reaction was started in the reactor by the bamboo within due to radiation and conduction of heat.

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Fig. 2 Bamboo and uploading to produce biochar

The TCPS 657-2547 [10] and the TCPS 658-2547 [11] standards, which are used as the standards for biochar used as fuel for cooking and grilling in Thailand, respectively, were compared to the properties of the bamboo biochar obtained, including moisture content (ASTM D 3173), ash content (ASTM D 3174), and volatile matter (ASTM D 3175).

The pyrolysis reaction produces three different products: gas (CO, H_2, CH_4), liquid (wood vinegar), and solid (biochar). Eq. (1) through Eq. (4) may be used to compute the solid and liquid yields as well as the reactor efficiency [12]. In gas composition analysis, there were three repetitions. The Agilent 990 Micro GC was applied to determine the composition of H_2, O_2, N_2, CH_4 and CO in the gas samples, which were collected using the 1-liter gas bag (SamplePro Flexfilm Bag) during the experiments. Furthermore, the pH of the liquid products produced by the reaction was measured with the Mettler Toledo (Seven Compact S220).

$$y_{char} = \frac{m_{char}}{m_{bio}} \quad (1)$$

$$\eta_{char} = y_{char} \times \left(\frac{HHV_{char}}{HHV_{bio}} \right) \quad (2)$$

$$Gaseous\ product = wt.\ of\ raw\ materials - wt.\ of\ solid\ and\ liquid\ products \quad (3)$$

$$HHV = 0.3536FC + 0.1559VM - 0.0078Ash \quad (4)$$

Where y_{char} is the biochar yield, -;
η_{char} is the pyrolyzer's efficiency, -;
m_{char} is the biochar dry mass, kg;
m_{bio} is the feedstock dry mass, kg;
HHV is the higher heating value, MJ/kg;
FC is the fixed carbon, wt % (as dry basis);
VM is the volatile matter, wt % (as dry basis);
Ash is the ash content, wt % (as dry basis).

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3. Result and Discussion

3.1 Experimental Results

Biochar was made by placing 332 kg of bamboo inside a reactor. Temperature measurements were recorded inside the reactor and of the gas that passed through the cooling tower until the experiment ended as illustrated in Fig. 3, when the firewood was lit at the bottom of the reactor to produce heat. This was found that the reaction could divided into three stages based on the temperatures of the cooled gas and internal reactor:

Stage 1 Reactor heating (0–140 minutes): The temperature rose to 450 °C, while the gas that had cooled down was 87 °C. Gas products from the breakdown of volatile compounds started to occur at this early stage. In order to determine the gas composition and heating value, a sample of gas was taken at 76 minutes, as indicated in Table 1. At 28.3%, nitrogen made up the majority of the gas composition, and its high heating value (HHV) was 4.59 MJ/Nm^3. The high nitrogen content, which was most likely caused by remaining air in the reactor at the beginning, prevented the gas from igniting, though.

Stage 2 Pyrolysis process (140-334 minutes): The temperature varied between 450 °C and 595 °C, reaching its highest point at 277 minutes. Smoke at this stage revealed a significant amount of volatile compounds. Reduced quantities of nitrogen and oxygen were observed in a gas sample obtained at 180 minutes (reactor temperature 475 °C, cooled gas temperature 89 °C), whereas concentrations of gases that produce energy, such as CH_4, CO, and H_2, which have higher heating values (HHV) at 282,990 kJ/kg mol, 285,840 kJ/kg mol, and 890,360 kJ/kg mol, respectively. As a result, the HHV of cooled gas increased to 9.74 MJ/Nm^3, which decreased the requirement for bamboo (as the fuel for heating) input by allowing the gas to ignite and potentially sustain the heat of the reactor by itself.

The gaseous samples were collected during Stage 1 (76 minutes at 300°C) and Stage 2 (180 minutes at 475°C) of the experiment. Due to the bamboo contains 12–28% lignin and 31-46% cellulose [7, 8], and because of the different bond breakdown temperatures of these components during the pyrolysis process. Therefore, the gaseous samples were collected at each stage. For lignin and cellulose, the temperature ranges for bond breakdown are specifically 250°C to 500°C and 275°C to 350°C, respectively [4]. As a consequence, the more smoke was generated during Stage 2, which was at 475°C, indicating an increased probability that the bamboo's lignin and cellulose were breaking down.

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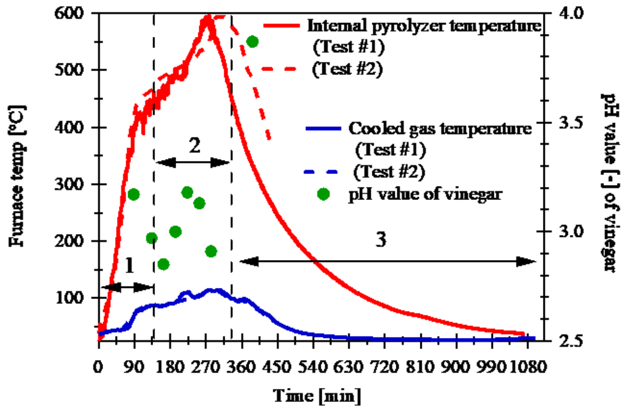

Fig. 3 Temperature profiles in the drum pyrolyzer and the cooled gas

Table 1 Gas compositions at different pyrolyzer temperatures

Time (min)	76 (Stage 1)	180 (Stage 2)
Internal pyrolyzer temp. (°C)	300	475
Cooled gas temp. (°C)	49	89
H_2 (vol. %)	3.66 ±0.25	11.36 ±0.82
O_2 (vol. %))	3.80 ±0.54	1.47 ±0.19
N_2 (vol. %))	28.34 ±3.20	4.48 ±0.65
CH_4 (vol. %).)	4.54 ±0.31	13.57 ±0.91
CO (% vol.)	21.56 ±1.87	29.86 ±1.76
HHV* (MJ/Nm^3)	4.59	9.74
	Non-ignited	Ignited

* HHV calculated according to Homdoung et al. [12]

Stage 3 Cool down (334-1060 minutes): After reaching a peak temperature of 595°C at 334 minutes, the temperature progressively declined to 451 °C as the pyrolysis reactions reduced and less volatile matter was released as smoke. As soon as the reactor's inside reached room temperature, the pyrolyzer was opened. To enable more examination, the bamboo biochar was taken out.

In the biochar production experiments, two tests were conducted (Test #1 and Test #2) with

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temperature results during the process shown in Fig. 3. The temperature difference between the reactor's internal temperature and the recirculating gas temperature (in the range of 100 °C - 595°C) between the two experiments varied from -9.1% to 9.8% and -12.9% to 0.3%, respectively. However, during the post-pyrolysis cooling period (Stage 3), in range of 375 - 430 minutes, the reactor's door used for bamboo loading and unloading began to deform due to prolonged heat exposure. This allowed air to continuously enter the reactor, causing the internal temperature to cool more rapidly. Nevertheless, the trends of both the reactor's internal temperature and recirculating gas temperature during the pyrolysis process period (Stage 1 and Stage 2) were similar and occurred within the same reaction range. As a result, Tables 1 and 2 present the results of the sample analysis and the discussion above using the data from the first experiment (Test #1).

Samples of wood vinegar that condensed from the condenser were collected during the experiment. Once the reactor's internal temperature reached 400 °C, sampling for the pH measurement started, and samples were taken every 30 to 45 minutes after that. The wood vinegar had a pH range of 2.85 to 3.18 when the reactor temperature was between 400 °C and 567 °C, according to the pH measurement data (as shown in Figure 3). The pH value increased to 3.87 when the reactor temperature dropped to 331 °C during the cooldown phase (Stage 3). The temperature of the pyrolysis reaction influences the liquid products that are produced; the temperature range between 450 °C and 600 °C yields the maximum liquid product yield [4]. Fig. 4 displays samples of biochar from the reactor and wood vinegar samples collected during the process. Wood vinegar has the potential to increase tomato (Solanum lycopersicum L.) yields when used properly. Tomato yield can be increased by 44–45% when wood vinegar, which has a pH of 3.09, is diluted with water at a ratio of 1:800 by volume and applied as a foliar spray and soil drench [13]. Furthermore, when sprayed in the field at a rate of 5,700 liters per hectare, wood vinegar with a pH of 3.3 can reduce weeds like perilla mint, Carolina geranium, and creeping woodsorrel by roughly 70–90% in just three days [14].

The current study used a drum pyrolyzer to examine the properties of bamboo and the products obtained from it. With a higher heating value (HHV) of 19.1 MJ/kg, the raw bamboo material had 11.1% moisture content, 78.0% volatile matter, 19.8% fixed carbon, and 2.2% ash content (as indicated in Table 2). When the bamboo was pyrolyzed at temperatures between 450 °C and 595 °C, significant changes in its characteristics were observed.

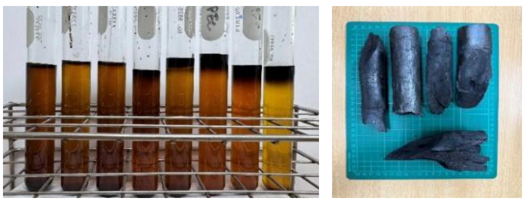

Fig. 4 Bamboo vinegar and bamboo biochar

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The significant drop in moisture content from 11.1% to 4.94% suggests that the pyrolysis procedure effectively dehydrated the material. For the generated biochar to have better fuel quality and longer storage stability, this moisture content reduction is essential.

The volatile matter level of the raw bamboo dropped dramatically to 39.2% from 78.0% in the biochar. This reduction, which indicates the release of volatile organic molecules during pyrolysis and the resulting creation of a more carbon-rich substance, is expected and desirable. On the other hand, the fixed carbon content rose significantly from 19.8% to 52.4%, indicating that the biochar structure contains a significant amount of carbon. Given that increased heating value and better fuel quality are correlated with this rise in fixed carbon, it is very significant.

Compared to the raw bamboo (2.2%), the produced biochar (8.4%) had a higher ash percentage. This increase, which is frequently seen in pyrolysis processes, is explained by the concentration of inorganic materials rising as the volatilization of organic matter occurs. Following the TCPS 658/2547 standard, the biochar used in this study had a high enough ash content to be used for grilling. However, the result closely approximated the cooking-related TCPS 657/5247. In raw bamboo, the higher heating value (HHV) of the biochar improved to 24.6 MJ/kg from 19.1 MJ/kg, a 28.8% improvement. One of the main benefits of the pyrolysis process is the increase in energy density, which makes biochar a more effective fuel source.

The pyrolysis procedure produced 55 liters of liquid (vinegar) and 115 kg of biochar as product yields. These results translate into a gas yield of 48.8%, a liquid yield of 16.6%, and a biochar yield of 34.6%. Based on the equation (2), the energy conversion efficiency for this experiment was at 44.6. The raw bamboo's high volatile matter content (78.0%) is responsible for the high gas output. These volatiles are released and transformed into gaseous products during pyrolysis, which explains the significant gas percentage.

The 34.6% biochar yield derived from this study was less than that of the study of Jarawi and Jusoh [9] (50.2%), but the result was similar to that of Kurimoto et al. [8] (40.7%). Differences in the pyrolysis conditions and equipment design may be the cause of this variation.

The drum kiln employed in this study and by Jarawi and Jusoh [9] appeared to offer a good compromise between yield and biochar quality.

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Table 2 Properties of bamboo biochars at different temperatures

	Moisture (wt%)	**VM** (wt%)**	**FC** (wt%)**	**Ash** (wt%)**	**HHV** (MJ/kg)**	**Biochar (yield, %)**	**References**
Bamboo (Raw material)	11.1 ±0.25	78.0 ±0.20	19.8 ±0.17	2.2 ±0.04	19.1*	-	Present work
Biochars, Temperature (°C)							
450-595	4.94 ±0.37	39.2 ±3.73	52.4 ±3.81	8.4 ±0.08	24.6*	34.6	Present work
300-400	4.26	16.9	76.4	5.4	29.6*	- ***	[7]
400	4.80	22.3	75.2	2.5	30.0*	40.7	[8]
750	6.10	34.2	49.5	16.3	25.6	50.2	[9]
TCPS657/2547 for cooking	< 10	< 25	> 57	< 8	> 6000 kcal/g		[10]
TCPS658/2547 for grilling	< 8	< 8		< 3	> 7000 kcal/g		[11]

* HHV calculated according to Homduang et al. [12]

** Based on dry basis

*** Not specifie

Bamboo vinegar was produced with a liquid yield of 16.6% and may find use in other industries as well as agriculture. This moderate liquid yield indicates that a considerable amount of the volatile stuff is transformed into non-condensable gases, even though some condensable volatiles are obtained.

3.2 Economic Analysis

By producing both biochar and wood vinegar through the pyrolysis process, bamboo can be used as an alternative energy source. As such, the research includes an economic analysis to calculate the internal rate of return and payback period to make an investment decision.

Given that the reactor was constructed of rolled sheet metal, which can be harmed by excessive temperatures, the economic analysis's assumptions for the reactor's lifetime and project duration are one year. In the course of the project, the reactor operates twenty times a month and monthly repair fees apply. Not considered in the computation is the energy cost of employing a 0.37 kW water pump, which runs for just 6 hours every reactor cycle. Table 3 displays details of the costs required for the economic analysis.

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The method of calculating the internal rate of return is to find out the rate of return at which the Present Worth of Disbursements (PWD) and the Present Worth of Incomes (PWR) are equal, as indicated by Eq. (5) and Eq. (6) [15]. The process of trial and error and interpolation to calculate the rate of return and arrive at a rate of return (i).

$$netPW = 0 = PW_R - PW_D \quad (5)$$

$$P = F\left[\frac{1}{(1+i)^N}\right] \quad (6)$$

Where PW_R is the present worth of incomes, Baht;
PW_D is the present worth of disbursements, Baht;
P is the present worth, Baht;
F is the future worth, Baht;
i is the interest rate, %;
N is the number of compounding periods, 12 months.

Based on the costs and income listed in Table 3, an analysis of the cash flow generated by the project over a one-year period is presented in Table 4 and Fig. 5(a). As seen in Fig. 5(b), the project generates an internal rate of return of 46.75% each month when the net cash flow for each month is computed as present value and the internal rate of return can be determined using Eq. (5) and Eq. (6). Moreover, the project will start to recover its investment at the beginning of the third month, based on Table 4's cumulative cash flow. Investment in the production of biochar and wood vinegar from bamboo is feasible and interesting due to its high returns and short payback period, as can be seen from the internal rate of return and the payback period indicated.

The production cost for biochar and wood vinegar is 2,956 Baht per operation, divided into 1,998 Baht for biochar and 958 Baht for wood vinegar, based on the data as indicated in Table 3. When calculated as production costs, biochar and wood vinegar are at 17.4 Baht/kg and 17.4 Baht/liter respectively. This results in higher profits from selling wood vinegar compared to biochar. However, since wood vinegar still requires quality improvement processes and packaging, which are outside the assumptions of this research, the cost of wood vinegar may increase further.

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Table 3 Cost and revenue estimation for bamboo biochar using a drum pyrolyzer

Category	Estimation (Baht)	Description
Pyrolyzer drum	-100,000	1 unit/12 months
Condensor unit	-32,000	1 unit/12 months
Other materials	-10,000	1 unit/ 12 months
Labour	-400/person	2 persons/operation
Maintenance cost	-15,000	1 unit/month
Bamboo for heat resource	-2 Baht/kg	75 kg/operation
Bamboo for making biochar	-2 Baht/kg	332 kg/operation
Biochar	21 Baht/kg	115 kg/operation
Vinegar	60 Baht/litre	55 litre/operation
Salvage	5,000	1 unit/12 months

Table 4 Monthly cash flow for bamboo biochar production

End of month	Income (Baht)	Disbursement (Baht)	Balance (Baht)	Cumulative cash flow, (Baht)
0	0	-142,000	-142,000	-142,000
1	114,300	-47,280	67,020	-74,980
2	114,300	-47,280	67,020	-7,960
3	114,300	-47,280	67,020	59,060
4	114,300	-47,280	67,020	126,080
5	114,300	-47,280	67,020	193,100
6	114,300	-47,280	67,020	260,120
7	114,300	-47,280	67,020	327,140
8	114,300	-47,280	67,020	394,160
9	114,300	-47,280	67,020	461,180
10	114,300	-47,280	67,020	528,200
11	114,300	-47,280	67,020	595,220
12	119,300	-47,280	72,020	667,240

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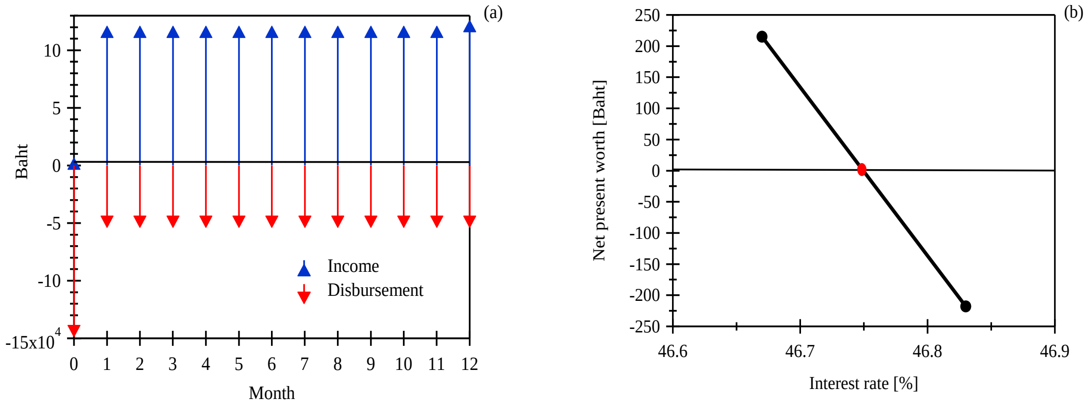

Fig. 5 Cash flow diagram for one year (a) and internal rate of return of the project (b)

For biochar, the selling price assumption used in this research is 21 baht/kg for wholesale, and profits can increase if retail sales are possible. On the market, biochar that can be utilized as an energy source prices between 35 and 45 Baht/kg. According to the costs involved in this study, producing biochar from bamboo in a drum pyrolyzer might be reasonably priced.

4. Conclusion

The present study concludes that the bamboo pyrolysis method, which applied a drum pyrolyzer, revealed an effective distribution of products and achieved a balance between the yields of liquid, gas, and biochar. The process yielded 34.6% biochar, 16% vinegar, and a noteworthy 48.8% gas while operating at temperatures between 450 °C and 595 °C. Energy recovery was made possible by the high gas production, which is linked to the high volatile matter content of the bamboo. When compared to raw bamboo, the resulting bamboo biochar had considerable improvements in fixed carbon content and heating value, displaying a heating value of 24.6 MJ/kg. Whereas this might not satisfy every strict standard for premium commercial biochar, this exhibits potential for a range of uses. With a monthly internal rate of return of 46.75% and a payback period of roughly two months based on a one-year project timetable, the procedure indicated potential from an economic standpoint. In order to further improve fixed carbon content and lower ash content and maybe achieve more exacting quality criteria for

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specific applications, future studies could concentrate on optimizing pyrolysis settings.

The steel reactor was found to have problems during the experiment, especially at the door where bamboo was loaded and bamboo charcoal was unloaded at the end of the operation. Temperatures can rise to about 600°C during the pyrolysis process, and materials that are exposed to heat for long periods of time might deform and damage. Long-term exposure to high temperatures also caused holes to develop in the combustion chamber tube. As a result, different heat-resistant building materials, such stainless steel, need to be employed.

Thyrsostachys siamensis Gamble bamboo for 3 years old, which was utilized in this study. However, the age and species of bamboo could have an impact on the characteristics of charcoal, such as their ash content and heating value. Therefore, choosing a suitable species and age of bamboo to produce biochar could be considered.

5. Acknowledgement

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