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Technical, Financial and Environmental Assessment of Bio-oil Production from Pyrolysis of Pigeon Pea [*Cajanus cajan* (L.) Millsp.] Wood

ABSTRACT

Pigeon pea (Cajanus cajan (L.) Millsp. wood was pyrolyzed using a semi-continuous gram-scale reactor at optimized conditions of temperature (469°C), nitrogen flow rate (14.2 mL min^{-1}), and particle size (1.3 mm), yielding bio-oil (54%), biochar (26%), and syngas (16%). The cost of bio-oil production for 1 t yr^{-1} was estimated to be US$ 681.00. Financial analysis revealed a net present value (NPV)of US$ 24,322.00 at 12% discount rate, an IRR of 343.85 %, with breakeven quantity of 199 L. Sensitivity analysis showed that an increased price of raw materials up to 30 %, and a decreased price of products down to 25 %, resulted to an increased NPV and IRR. Decreasing the bio-oil yield below 40 % gave a negative NPV with an IRR of 9%. If bio-oil and biochar were tapped as alternative bioenergy, 360,000 L of fuel oil and 259 t of coal could be saved. A total greenhouse gas emission of 749 t of CO_2 equivalent can be avoided. Thus, pigeon pea pyrolysis for bio-oil production provided a net positive energy output and was proven to be profitable investment, and environment-friendly as potential bioenergy resource to replace petroleum-based fuels.

Keywords: *Pigeon pea, pyrolysis, bio-oil, environment, techno-economic analysis*

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INTRODUCTION

The worsening environmental degradation as related to the use of fossil fuels, upsurge in energy demands and decline in petroleum reserves resulted to a growing interest globally to discover renewable, sustainable and cleaner alternatives for energy production (*Mehmood et al. 2017, Saikia et al. 2019*). Renewable energy has become more essential in addressing environmental issues over the use of fossil fuel and its role in climate change (*Do et al. 2014*). Biomass (i.e., plant materials and agricultural wastes) is well known as a primary source of renewable energy to augment the dwindling fossil fuel reserves (*Isahak et al. 2012*). Biomass is considered as a promising alternative source of clean and sustainable energy for the next generations. However, the cost of producing biomass-based energy depends on the cost of biomass used in the process (*Mehmood et al. 2017, Saikia et al. 2019*).

Pigeon pea [*Cajanus cajan* (L.) Millsp.] is a promising biomass or energy crop locally known as *kadios* (Tagalog) and *kardis* (Ilocano). The Philippines has substantial area (454 ha) of pigeon pea cultivation (*FAOSTAT 2018*), which was spread throughout Regions 1 to 4 and Bicol region. Pigeon pea is usually grown in backyards, marginal lands, on insignificant land portions, or even in abandoned fields. It grows fast with low maintenance cost when cultivated. It is a versatile crop since all its parts can be utilized as food (pods, seeds and leaves), forage/feed (pods and leaves), folkloric medicine (leaves, pods, seeds), fertilizer (dried leaves/hulls), fencing material (stalk), and fuel wood (*Tanquilut et al. 2019*). The International Crops Research Institute for the Semi-Arid Tropics (*ICRISAT 2013*) reported that approximately 15-20 t ha^{-1} of fuel wood from pigeon pea crop can provide energy at about 4,000 kcal kg^{-1}.

Pyrolysis is the thermal decomposition of chemical bonds of a target biomass material. Pyrolysis process occurs without oxygen, generating three main products namely: solid, made up mostly of carbon; non-condensable gas, which is combustible; and condensable gas to form pyrolysis liquid or bio-oil (*Demirbas and Arin 2002; Kung and Zhang 2015; Maguyon and Capareda 2013 and McKendry 2002*). For almost all types of biomass, pyrolysis is regarded as convenient, economical, and environmentally suitable biomass-to-energy conversion process (*Kilic et al. 2014; Saikia et al. 2019*).

Bio-oil is regarded as a potential substitute for petroleum fuels to generate power (e.g., high power diesel motors, boilers and turbines), heat, or for extraction of valuable chemicals. Its use is projected to contribute in supplying energy in the future. It also presents countless benefits compared to raw biomass as an energy product, that is, conversion of raw biomass into bio-oil has a positive net energy output. For example, its higher bulk density than raw biomass results to more convenient transportation and storage. Bio-oils are also CO_2/ greenhouse gas (GHG) neutral, do not generate SO_x, and emit less NO_x (50 %) than diesel oil, thus minimizing pollution than conventional oil. Bio-oil from pyrolysis of diverse agricultural residues has varied heating value of about 20 MJ kg^{-1}, almost the same as that of petroleum fuel, hence can be regarded as a promising fuel oil (*Kumar et al. 2010; Mohan et al. 2006 and Xiu and Shahbazi 2012*).

Biomass conversion has become a significant alternative to numerous applications including energy and chemical production. As such, biomass conversion must be economically viable and environmentally acceptable for it to be sustainable (*Basu 2013*).

A techno-economic assessment (TEA) is also known as techno-economic evaluation or techno-economic analysis. This is often linked to biomass utilization and more commonly used since 2010. A TEA is often carried out on new technologies that are designed for environmental purposes (*Kuppens et al. 2015*). Available literature on technologies using TEA are well-documented, as follows. Techno-economic analysis of bio-oil from corn (*Zea mays*) stover fast pyrolysis was examined including its subsequent upgrading to transportation fuel, that is, naphtha and diesel range fuels (*Wright et al. 2010*). *Do et al.* (*2014*) evaluated the financial feasibility of bio-oil production process from empty fruit bunches via fast pyrolysis using a fluidized-bed reactor. *Farag and Chaouki* (*2015*) studied the economic evaluation for on-site pyrolysis of kraft lignin to value-added chemicals. *Kung and Zhang* (*2015*) also evaluated the economic and environmental aspects of renewable energy from pyrolysis using crops and agricultural residuals. Recent research has also included integrated assessments of bioenergy technology development. *Valente et al.* (*2011*) examined the environmental, economic, and social effects on the possible utilization of woody biomass as energy resource. *Ng et al.* (*2012*) reported the green potential of the palm biomass industry and at the same time safeguarding both environmental and ecological health, as well as promoting technology transformation. *Nanaki and Koroneos* (*2012*) evaluated the environmental, technical, and cost performance of biofuel using the life cycle analysis technique. According to *Kuppens et al.* (*2015*), *Tahon* (*2013*), and *Van Dael et al.* (*2014*), based on these examples, there were no hard rules in doing techno-economic evaluations which posed difficulty in using and comparing existing TEAs. They also stated that there should be a well-defined perception of the fundamental technology, the need to determine the heat and electricity requirements as well as mass and energy balances for biomass conversion technologies. Techno-economic assessment requires some indicators to determine if the technology is profitable and environment friendly. According to *Boardman et al.* (*2006*), the net present value (NPV) and the internal rate of return (IRR) are indicators whether the pyrolyzer technology is profitable or not. The IRR can only be used as a deciding factor in selecting projects when there is only one alternative, and is used in a group of mutually exclusive projects that differ in size. *Kuppens et.al.* (*2015*) concluded that in evaluating thermo-conversion technologies, only NPV is preferred. Typically because it provides absolute values that is related to level of investment and costs rather than relative indicators such as IRR or BCR.

Several studies on the TEA of bio-oil production through pyrolysis have been published, as discussed in the succeeding sentences, reporting various extents, feed stocks, and reflecting national cost structures (**Table 1**). Based on the study conducted by *Mullaney* (*2002*), bio-oil production costs depend on plant capacity, reactor type, operating conditions, and vapor residence time. Various feeds ranging from corn stover, wood chips, and

Table 1. Techno economic assessment of bio-oil production comparing plant size, bio-oil cost, and type of biomass feedstocks used in previous works and this present work.

Plant size (Biomass Input, t d^{-1})	Bio-oil cost (US\$ L^{-1})	Feed	Source
100	0.32	Wood chips	*Mullaney* (*2002*)
200	0.26	Wood chips	*Mullaney* (*2002*).
1000	0.16 - 0.65	Wood, peat, rice straw	*Solantausta et al.* (*1992*)
100-800	0.29 – 0.50 (\$12-26 GJ^{-1})	Energy crops (willow, silver grass)	*Rogers and Brammer* (*2012*)
20-24	0.08	Pigeon pea wood	This study

* Currency exchange rate: US$ 1.00 = PhP 56 (4th quarter of 2018)

rice (*Oryza sativa* L.) straw to energy crops were reported. In general, bio-oil production costs from US$ 0.1 to 0.6 L^{-1} depending on operating conditions used. For example, in the United States, a study was done on the conversion of low-grade wood chips to bio-oil, chiefly as a substitute for fuel oil, which can be used for furnace, boilers and engine. The bio-oil cost was estimated to be US$ 0.32 L^{-1} for 100 t d^{-1} plant size. In another study, *Solantausta et al.* (*1992*) reviewed 11 different pyrolysis variations in wood, peat and straw as potential feedstock. Bio-oil price ranged from US$ 117.00 to 488.00 t^{-1} of bio-oil. In the United Kingdom, *Rogers and Brammer* (*2012*) showed that the bio-oil production costs from fast pyrolysis of energy crops such as silver grass (*Miscanthus sinensis*) and willow (*Salix alba* L.) were estimated to be US$ 12 to 26 GJ^{-1}, with variable feed stocks and plant sizes. The two important factors impacting the production costs of bio-oil were electricity consumption and surplus char selling. In this present work, the suitability of Philippine pigeon pea wood for bio-oil production from pyrolysis process is considered using a laboratory-scale reactor. Such experiments have not been reported to date.

This study assessed the technical, financial, and environmental potential of bio-oil from pyrolysis of pigeon pea wood using a small semi-continuous gram-scale reactor. Specifically, this study aimed to analyze the production and energy consumption of bio-oil and biochar and assess the financial viability of bio-oil production from pyrolysis and examine its environmental impact. This study was conducted from September to December 2018.

MATERIALS AND METHODS

Technical Assessment

Raw pigeon pea wood samples were collected from the pigeon pea plantation in Magalang, Pampanga, Philippines. Good quality wood with at least 2-5 cm in diameter from the main branch/stem were used in the study. They were cut manually from the base by using a sharp bolo. Preliminary processing of pigeon pea wood entailed pre-processing cost which included chopping/chipping, drying (at least 10 % moisture content), grinding/milling, and sieving (particle size of 2 mm or less).

The experimental set-up in the pyrolysis of pigeon pea wood utilized a small gram-scale semi-continuous reactor. The machine is usually made of stainless steel equipped with fluidized sand bath heaters, automatic temperature control, and a nitrogen gas tank with gauge/controller. The products of pyrolysis of pigeon pea wood are the bio-oil (water free), biochar (ash free), and gas. Data generated from the pyrolysis runs were subjected for analysis using Box-Behnken three-level, three-factor fractional factorial design. It revealed the optimum condition of 469°C, particle size of 1.3 mm, and nitrogen flow rate of 14.2 mL min^{-1}, for maximum bio-oil yield (54 % w/w based on feed intake).

According to *Jaroenkhasemmeesuk and Tippayawong* (*2015*), the calculation on mass balance and energy conversion provides the theoretical basis for actual production to improve economic effectiveness. Mass balance is essential in controlling the processing, particularly the products of pyrolysis. Energy balance optimizes the operation cost and manages energy being used, wasted or lost.

The weight of raw pigeon pea wood before pyrolysis as well as the weight of bio-oil and other products of pyrolysis were obtained. Mass balance was carried out based on the optimum yield and the mass conversion (%) for each product of pyrolysis, and was calculated using the equations 1a to 1c. Equation 2 was considered for the mass balance.

$$\%Bio\ Oil\ Mass\ Conversion = \frac{m_{bo}}{m_{pw}}\ x\ 100 \tag{1a}$$

$$\%Biochar\ Mass\ Conversion = \frac{m_{bc}}{m_{pw}}\ x\ 100 \tag{1b}$$

$$\%Gas\ Mass\ Conversion = \frac{m_{gas}}{m_{pw}}\ x\ 100 \tag{1c}$$

$$m_{in} = m_{out}$$

$$m_{N2} + m_{pw} = m_{bo} + m_{bc} + m_{gas} \quad (2)$$

where: m_{bo}- mass of bio-oil produced, g
m_{bc}- mass of biochar produced, g
m_{gas}- mass of gas produced, g
m_{pw}- mass of pigeon pea wood (biomass), g
m_{N2} – mass of nitrogen gas, g

From schematic diagrams of mass balance for pyrolysis of pigeon pea wood the optimum bio-oil yield was 54 %, while the yields of biochar and gas were 26% and 16 %, respectively, with a small loss of 4 % (**Figure 1**).

As for the energy conversion, equation 3 was used in the calculation. This parameter is basically the sum of the mass of pyrolytic products multiplied by its energy content divided by the product of the mass of the biomass and its energy content. The respective heating values of bio-oil, biochar and gas vary for the mass balance and energy conversion on the pyrolysis of pigeon pea wood (**Table 2**).

$$\%\,Energy\,Conversion = \frac{\sum[(m_{bo}\,x\,HV_{bo}) + (m_{bc}\,x\,HV_{bc}) + (m_{gas}\,x\,HV_{gas})]}{(m_{pw}\;x\;HV_{pw}) + E_{system}} x100 \quad (3)$$

where: HV_{bo}- heating value of bio-oil, MJ kg^{-1}
HV_{bc} – heating value of biochar, MJ kg^{-1}
HV_{gas} – heating value of gas, MJ kg^{-1}
HV_{pw} – heating value of the biomass, MJ kg^{-1}

Table 2. Mass and heating value needed for the mass balance and energy conversion on the pyrolysis of pigeon pea wood.

Item	Value
Mass of pigeon pea wood (kg)	1
Mass conversion on bio-oil yield (%)	54
Mass conversion on biochar yield (%)	26
Mass conversion on gas yield (%)	16
Heating value of pigeon pea wood (MJ kg^{-1})	17.33
Heating value of bio-oil (MJ kg^{-1})	28.78
Heating value of biochar (MJ kg^{-1})	26.21
Heating value of gas (MJ kg^{-1})	6.98

Regarding the percent energy conversion of the pyrolysis system (**Figure 2**), the energy input, namely the pigeon pea wood and the pyrolysis system were 73.5 % and 23.5 %, respectively. The energy output consisted of the percent energy converted for bio-oil (66 %), biochar (29.3 %), and gas (4.7 %). Nitrogen gas was assumed to be negligible since it was added for the purpose of purging any oxygen content in the system, but was also removed prior to pyrolysis.

Economic Assessment

Some financial indices were determined to evaluate the economic viability of bio-oil production from pigeon pea wood. These included the costs and returns, return on investment (ROI), NPV, payback period (PBP), and IRR.

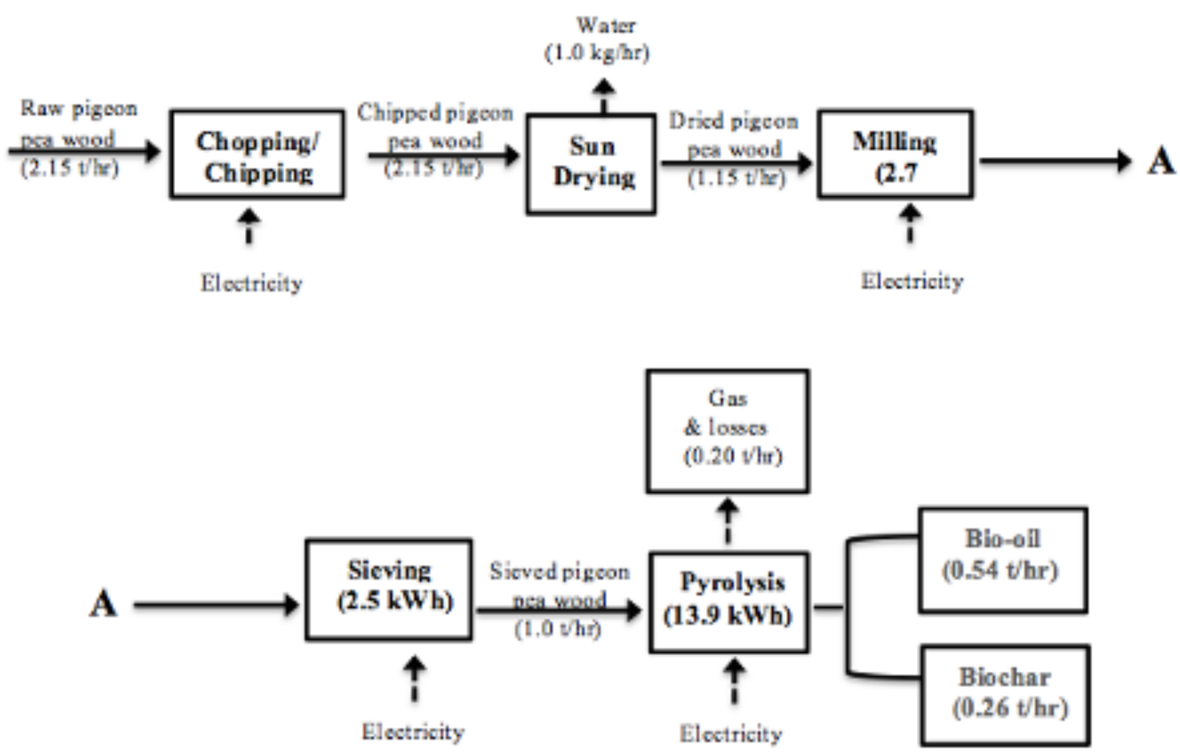

Figure 1. Process flow chart showing material conversion/balance for the pyrolysis of pigeon pea wood.

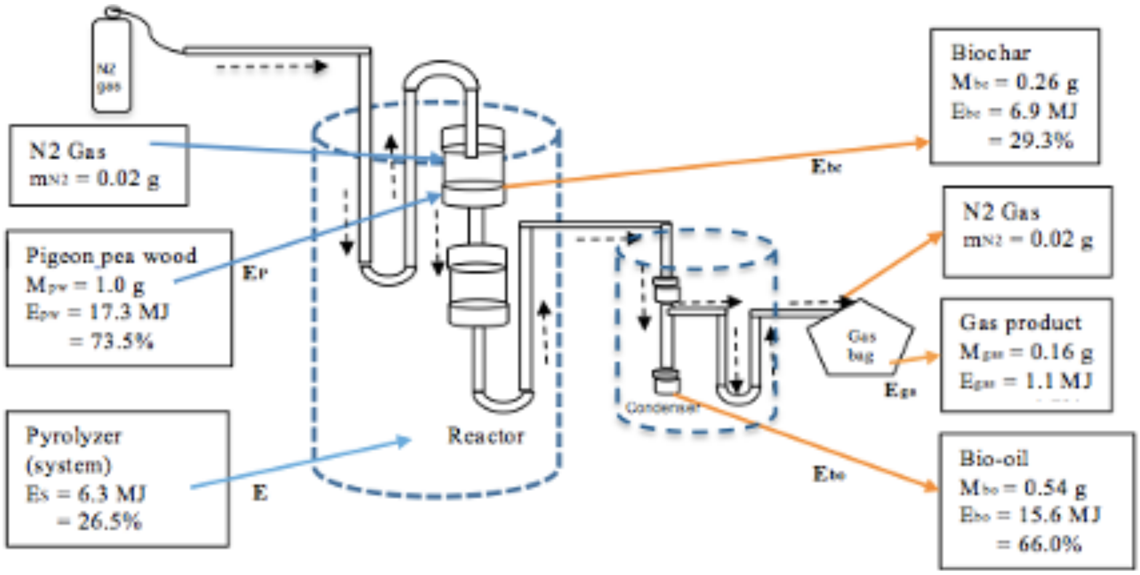

Figure 2. Schematic diagram of gram-scale pyrolyzer showing material conversion and energy balance during pyrolysis of pigeon pea wood.

A sensitivity analysis was done to identify the key factors that may have major influence in the costs and benefits, and to make the most realistic assumptions. This economic assessment focused on the financial profitability of the investment and the benefits that can be realized by small-scale growers/farmers and processors of pigeon pea.

The work of *Wright et al.* (*2010*) was used as basis for the total capital and production cost estimates. Twenty tons of pigeon pea wood per year was considered as an input. The optimum bio-oil yield of pigeon pea wood was 54% with a specific gravity of 1.2. With an assumed operation time of 4,000 hr y^{-1}, the estimated annual bio-oil production is 9 t, while the biochar yield is 5 t yr^{-1}. The capital (investment) cost of the pyrolysis system was estimated as US$ 2,046.00 (**Table 3**). The cost of raw pigeon pea wood is US$ 11.00 t^{-1}, which was based on the prevailing price of fuel wood in Pampanga, Philippines, as its market price (pick up cost of US$ 0.01 or PhP 0.63 kg^{-1}). Sun drying was carried out, and the labor in collecting and sun drying the raw pigeon pea wood was considered as its drying cost. The total fixed cost is US$ 1,135.00, which included the depreciation, repair and maintenance, insurance and building rentals. The total variable cost was US$ 3,055.00, which consisted of the raw pigeon pea wood, as well as materials needed during pyrolysis such as nitrogen gas, bottle containers, gas bag, gas containers. The operational cost of US$ 7,384.00 covered the cost for labor, energy and utilities. The labor and energy costs included that for grinding, milling, sieving and pyrolyzing. Other operating costs such as research, distribution and marketing costs were not included in the calculation. Since the reactor is only a small unit which required limited space, it was assumed that land rentals/acquisition be excluded also from the fixed costs. Total cost of production was computed to be US$ 681.00 t^{-1} of oil.

Table 3. Assumptions on the cost and return analysis of bio-oil production from pyrolysis of pigeon pea wood.

Item	Value*
Useful life of pyrolysis system (yr)	15
Operation Time (hr yr^{-1})	4,000
Material Input (t yr^{-1})	20
Raw Pigeon Pea Wood (US$ t^{-1})	11
Capital (Investment) Cost (US$)	2,046
Fixed Cost	
Depreciation (US$ yr^{-1})	161
Repair and maintenance (US$ yr^{-1})	206
Insurance (US$ yr^{-1})	41
Building rentals (US$ yr^{-1})	729
Operation Cost	
Labor Cost (US$ yr^{-1})	6,607
Energy Cost (US$ yr^{-1})	569
Utilities (US$ yr^{-1})	208
Variable Cost (US$ yr^{-1})	
Pigeon pea wood (US$ yr^{-1})	224
Other consumables	2,831
Cost of Bio-oil Production (US$ t^{-1} oil)	681
Yield of Bio-oil (t oil yr^{-1})	9
Yield of Biochar (t yr^{-1})	5
Selling Price of Bio-oil (US$ L^{-1})	0.98
Selling Price of Biochar (US$ kg^{-1})	0.64

* Based on Biomass Technology Group (BTG, The Netherlands) pilot and scale down with 0.7 rule.

Environmental Assessment

Bio-oil production was measured in terms of reduction in the greenhouse gas emission using electricity. The power capacity and gross generation according to fuel types in 2016 was used as basis to compute the kg GHG emissions kWh from grid (*ADB 2017, Aquino 2017, IPCC 2007, PEC 1999, and Posadas 2017*) (**Table 4**). The energy input requirement during pyrolysis as well as the energy output from products of pyrolysis (bio-oil and biochar) were also considered. Oil, whether it came from biomass or synthetic oil, has relatively higher environmental impact second only to coal (**Table 4**).

The comparison bio-oil and biochar with other sources of fuel products was used to compute the GHG emission for the production and utilization of bio-oil (and biochar), as well as that for fuel oil (and coal) (**Table 5**). The difference of these emissions is the amount of avoided emission. This shows that bio-oil from pigeon pea wood has the lowest heating value but has low GHG emission. Certainly, there is a trade-off. However, the GHG emission from fuel consumption appears not significantly different except fuel oil.

RESULTS AND DISCUSSION

Economic Assessment

The total annual cost, which consisted of investment, fixed, variable and operating costs amounted to US$ 13,619.00 (**Table 6**). The total annual revenue of US$ 10,662.00 and US$ 3,394.00 from bio-oil and biochar, respectively, which were obtained based on their existing rates. The annual net revenue of US$ 453.85, and the percent return on investment (ROI) is 21.38%. This reflects the high profitability of pyrolyzing of pigeon pea wood, since the average ROI is 15 % for a profitable investment, according to literature. This recommended ROI may be adopted for pyrolyzer technologies.

The break-even quantity refers to the rate where a certain level of bio-oil production and total income expenses are equal. This is quantity of bio-oil that must be produced to cover the operating cost. Given the price of US$ 0.98 L^{-1}, the sales volume should be 542 L to breakeven (**Table 7**). It also shows that 199 L of bio-oil should be produced in a year to break even, amounting to US$ 196. It took 50 d of operation to attain this, which is lower than the actual operating days of 250 d yr^{-1}. This further implied the very high profitability of the pyrolysis of pigeon pea wood. The payback period measures how fast an investment can be recovered in terms of number of years. Based on the analysis, the initial cost of the pyrolysis system can be recovered in 10 months only.

For the investment to be viable in the long run, the NPV must be positive (*Mojica and Elauria 2015*). With the NPV of US$ 24,322.00, with a discount rate of 12%, the investment is considered profitable and viable. The

Table 4. The greenhouse gas emissions from different types of fuel by source (from grid in 2016) with power generated, efficiency and heating value.

Type of Fuel By Source	Power Generated GWh	Efficiency %	Mean Heating Value MJ kg^{-1}	Life Cycle GHG kg CO_2 Eq kWh	GHG Emission Mg CO_2 Eq
Coal	43.31	30-35	28.50	0.97	41,842.82
Oil Based	5.63	30-35	43.60	0.77	4,309.60
Natural Gas	19.88	45-50	51.90	0.52	10,316.70
Geothermal	11.08	45-50	-	0.02	166.49
Hydro	8.08	85	-	0.01	90.99
Biomass	0.73	17	20.50	-	-
Solar	1.09		-	-	-
Wind	1.00	23	-	0.03	29.46
Total	90.80				56,756.06
kg GHG emissions CO_2 equivalent kWh (from grid)					0.63

Sources: *ADB 2017, Aquino 2017, Posadas 2017*

Table 5. Comparison of products of pyrolysis from pigeon pea wood with other sources of fuel in terms of its heating value, greenhouse gas (GHG) emission from fuel consumption as well as life cylce GHG emissions.

Type of Fuel	Mean Heating Value	GHG Emissions from Fuel Consumption	Life Cycle GHG Emissions
Fuel oil (bunker)	40.85 MJ L^{-1}	3.18 kg CO_2 Eq L^{-1}	3.42 kg CO_2 Eq L^{-1}
Bio-oil (pigeon pea)	24.99 MJ L^{-1}	2.11 kg CO_2 Eq L^{-1}	2.19 kg CO_2 Eq L^{-1}
Coal (bituminous)	28.50 MJ kg^{-1}	2.71 kg CO_2 Eq kg^{-1}	2.77 kg CO_2 Eq kg^{-1}
Biochar (pigeon pea)	27.99 MJ kg^{-1}	2.66 kg CO_2 Eq kg^{-1}	2.72 kg CO_2 Eq kg^{-1}

Source: *ADB 2017*

Table 6. The profitability analysis for bio-oil production from pyrolysis of pigeon pea wood.

Item	Amount
Total Revenue (US$ yr^{-1})	
Revenue from Bio-oil (US$ yr^{-1})	10,662
Revenue from Biochar (US$ y^{r-1})	3,394
Total Cost (US$M yr^{-1})	13,619
Net Revenue Before Tax (US$ yr^{-1})	453.85
Return on Investment (%)	21.38

* Currency exchange rate: US$ 1.00 = PhP 56 (4th quarter of 2018)

Table 7. The break-even analysis for bio-oil production from pyrolysis of pigeon pea wood.

Items	Amount
Average Fixed Cost (US$)	1,135
Variable Cost per unit (US$ L^{-1})	7
Selling Price Bio-oil (US$ L^{-1})	0.98
Optimum Yield of Bio-oil (%)	54
Sales Volume (L)	542
Break Even Quantity (L)	199
Break Even Value (US$)	196

* Currency exchange rate: US$ 1.00 = PhP 56 (4th quarter of 2018)

IRR is 343.85 % at optimum yield of bio-oil at 54%, which is greater than the opportunity cost of capital (12%). The annual net revenue and the ROI also reflect the high profitability of pyrolyzing of pigeon pea wood (**Table 6**).

In the sensitivity analysis, different indicators, namely: price of the products, price of raw pigeon pea wood, and optimum yield of bio-oil were considered. Any change in the values of any of these indicators will affect the average net revenue, ROI, NPV, and IRR. Decreasing the price of the product down to 25% and increasing the price of raw pigeon pea wood up to 30% brought a reduction in the average net revenue and ROI, but an increase in the NPV, and IRR (**Table 8**).

Decreasing the bio-oil yield less than its optimum yield at 54% may result to negative values for the annual net revenue and ROI (**Table 9**). The bio-oil yield was decreased below 40%, the NPV is negative, and its IRR is 9% when NPV is zero.

Environmental Assessment

The concept of carbon neutrality of biomass was also considered in this study. The carbon dioxide (CO_2) released during the combustion of biofuels is taken up by plants for photosynthesis, thus balancing the CO_2 cycle (*Dhyani and Bhaskar 2018*). According to *Abbasi and Abbasi* (*2010*), fossil fuels are considered 'carbon positive', while biomass is 'carbon neutral'. *Abbasi and Abbasi* (*2010*) stated that its use as fuel, directly or after conversion to other forms, must release only a certain amount of CO_2 needed by the biomass for its growth. This reasoning of 'carbon neutral' nature of biomass energy has recreated interest worldwide to utilize biomass as a source of liquid fuels (methanol, ethanol, biodiesel, etc.) to substitute petrol and diesel.

Table 8. The sensitivity analysis due to decrease in selling price of bio-oil and increase in the price of raw pigeon pea wood.

Financial Parameter	Base Value	Decrease in Selling Price of Bio-oil				
		-5 %	-10 %	-15 %	-20 %	-25 %
		Increase in Price of Raw Pigeon Pea Wood				
		5 %	10 %	15 %	20 %	30 %
Annual Net Revenue (US$)	437	437	436	435	434	432
ROI (%)	21.38	21.34	21.30	21.26	21.21	21.13
NPV (US$) at 12% DR*	24,322	24,342	24,361	24,381	24,401	24,441
IRR (%)	343.85	343.87	343.88	343.89	343.90	343.93

* Currency exchange rate: US$ 1.00 = PhP 56 (4th quarter of 2018); DR – discount rate

Table 9. Summary data on the sensitivity analysis due to decrease in bio-oil yield from pigeon pea wood.

Financial Parameter	Base Value	Decrease in Bio-oil Yield				
		50 %	45 %	40 %	35 %	30 %
Annual Net Revenue (US$)	437	-389	-1,372	-2,356	-3,340	-4323
ROI (%)	21.38	-19	-67	-115	-163	-211
NPV (USS) at 12% DR*	24,322	18,019	10,516	3,013	-4,490	-1,194
IRR (%)	343.85	155	69	27	-18	-

* Currency exchange rate: US$ 1.00 = PhP 56 (4th quarter of 2018); DR – discount rate

The projected amount of bio-oil and biochar from pigeon pea wood produced by pyrolysis were 589,000 L and 264 t, respectively. This gave 0.6 kg GHG emissions CO_2 equivalent per kWh (**Table 10**). The total GHG emissions of CO_2 equivalent from energy input during pyrolysis and the energy output from bio-oil was 107 t and that of biochar was 137 t. This resulted to an emission savings of 244 t CO_2 equivalent per year. If bio-oil and biochar were tapped, 360 m^3 of fuel oil and 259 t of coal could be saved. The total emission from fuel oil and coal for its production/utilization was 2,966 t of CO_2 eq. While the total emission from bio-oil and biochar was 2,217 t CO_2 eq. The difference of this was the avoided GHG emission of 749 t of CO_2 eq.

Table 10. The total greenhouse gas emissions from the production and utilization of bio-oil and fuel oil.

Items	Amount
Volume of bio-oil produced from pyrolysis (L)	589,000
Amount of biochar produced from pyrolysis (t)	264
Volume of fuel oil displaced (L)	360,000
Amount of coal displaced (t)	259
Total emission from fuel oil (and coal) for its production/utilization (t CO_2 eq.)	2,966
Emission from the production of fuel oil (t CO_2 eq.)	215
Emissions from consumption of fuel oil (t CO_2 eq.)	2,017
Emissions from consumption of coal (t CO_2 eq)	733
Total emission from bio-oil (and biochar) for its production/utilization (t CO_2 eq.)	2,217
Emission from energy input (electricity) for pyrolysis (t CO_2 eq.)	107
Emissions from use of bio-oil (t CO_2 eq.)	1,390
Emissions from use of biochar (t CO_2 eq.)	721
Avoided GHG emission (t CO_2 eq.)	749

CONCLUSIONS AND RECOMMENDATION

The technical and financial analysis of bio-oil production from pyrolysis of pigeon pea wood indicated that the investment was profitable and viable. The investment has an ROI of 21.38%, payback period of 10 months, NPV of US$ 24,322.00 at 12% discount rate, and IRR of 343.85 %, respectively. Sensitivity analysis showed that an increase in price of raw materials up to 30 %, and a decrease in the price of products down to 25%, brought a reduction in the average net revenue and ROI, but an increase in the NPV, and IRR. If the bio-oil yield was decreased below 40%, the NPV is negative, and its IRR is 9% when NPV is zero.

The technology is also environment friendly since it greatly reduced CO_2/GHG emissions. If the bio-oil and biochar were used as an alternative source of energy, 360,000 L of fuel oil, and 259 t of coal can be saved. A total GHG emission of 749 tons of CO_2 equivalent can be avoided. Based on these findings, bio-oil production from 1 t of pigeon pea wood was proven to be a very profitable investment and environment friendly. Therefore, to maximize the potential of bio-oil from pigeon pea wood, the biomass processing or pre–treatment and raw bio-oil properties should be improved. The use of catalyst or hydro-treatment or hydro-cracking, and upscaling of the pyrolysis system to improve raw bio-oil properties for industrial purposes is recommended. However, these may entail additional operation cost.

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