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Environmental and economic analysis of a biodiesel power plant derived from the fast pyrolysis of empty fruit bunches

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Abstract

As a major waste biomass from the palm oil mill process, empty fruit bunches (EFBs) are a potential energy source. This study analyses the environmental and economic impact of biofuel in the fast pyrolysis of EFBs to produce 100 kW of electricity. Aspen Plus commercial simulation provided 100 tons/day of dried EFBs to produce bio-oil, char, and gas at 74.4, 12.1, and 13.5 tons/day, respectively. From the economic perspective, the net present value (NPV), internal rate of return (IRR), and payback period (PBP) for this number of EFBs equate to USD10.71 M, 10.4%, and 13.18 years, respectively, based on 20 years of life and a total capital investment of USD36.26 M. The PM2.5 formation from the process is 19.6 tons PM2.5 eq (equivalent)/year in terms of environmental impact. In addition, the process results indicate significant greenhouse gas emissions of 44,608 tons CO_2 eq (carbondioxide equivalent)/year. In comparison, landfill or direct EFB combustion can reduce CO_2 emissions by 69,964- and 10,446-tons CO_2 eq/year, respectively. Damage to human health, represented by disability-adjusted loss of life years, is about 0.11, while damage to ecosystem diversity, representing species loss during a year, is around 0.125. In both cases, the damage incurred by EFB fast pyrolysis is lower than landfill and direct EFB combustion.

Keywords: Aspen plus process modelling, Bio-oil production process, Bio-oil upgrading process, Empty fruit bunches, Fast pyrolysis

1. Introduction

In Thailand, oil palm is considered the most important commercial oil crop due to its wide range of industrial uses, such as in the food industry to produce margarine, cooking oil, desserts, and in the commodity market to produce cosmetics, soaps, or candles. Moreover, palm oil can also be used as an alternative renewable energy source to produce biodiesel. Thailand is the third-largest oil palm producer in the world after Indonesia and Malaysia. Therefore, large quantities of empty fruit bunches (EFBs) are collected from palm oil mill plants. In 2019, the Office of Agricultural Economics reported oil palm availability of around 16.8 M tons, around 23-25% of which came from EFBs [1]. Commonly used as a direct fuel or converted into renewable energy to replace fossil fuels and reduce methane gas emissions, EFBs help mitigate climate change from waste landfills. The conversion of biomass into energy involves three technological processes: biochemical, thermochemical, and physio-chemical. Pyrolysis is a thermochemical decomposition process for converting biomass into biofuel. EFBs are raw materials and a type of lignocellulose biomass containing cellulose, hemicellulose, and lignin. The EFB pyrolysis process yields char, a carbonaceous residue, non-condensable gas, and liquid biofuel called "Bio-oil." [2]. Fast pyrolysis produces the highest liquid bio-oil yield of 60-75 wt compared to slow and intermediate pyrolysis. It is operated at atmospheric conditions and a moderate temperature of around 500℃ without oxygen, and at very short residence times [3]. Since this process is designed to maximise bio-oil yield, fast pyrolysis is used in the bio-oil production process. The bio-oil product obtained from pyrolysis requires upgrading by hydrotreatment due to its poor physical properties (e.g., low heating value, high viscosity, high oxygen content, low volatility, and corrosiveness). The treated bio-oil can be used as fuel for transportation (diesel and gasoline) or to generate electricity (e.g., diesel engines, gas turbines, and natural gas/steam power plants) [4]. This study aims to examine the economic viability and environmental impact of this biodiesel power plant from EFB pyrolysis perspective by developing a process simulation model for bio-oil production from EFBs while using the bio-oil upgrading process in Aspen Plus V.11.0 software for monitoring 100 kW power generation.

2. Materials and methods

2.1 Materials

As raw materials for the pyrolysis process, the properties of EFBs can be utilised in various applications, as reported in [5]. These researchers analysed the proximate and ultimate composition (e.g., carbon, hydrogen, nitrogen, and sulphur) of the EFBs collected from the palm oil mill in Chonburi Province, Eastern Thailand according to the American Standard Test Method. The EFB properties are presented in Table 1. The feeding rate of EFBs in this process is fixed at 100 tons/day (dried basis) to produce biodiesel and gasoline.

Table 1 Proximate, ultimate, and biochemical properties of EFBs (air-dried) in Chonburi Province, Thailand [5].

Properties	Unit	Value
Proximate composition		
- Moisture	% wt.	8.34
- Volatile matter	% wt.	73.16
- Fixed carbon	% wt.	12.20
- Ash	% wt.	6.30
Ultimate composition		
- Carbon atoms (C)	% wt.	50.63
- Hydrogen atoms (H)	% wt.	6.20
- Oxygen atoms (O)	% wt.	42.64
- Nitrogen atoms (N)	% wt.	0.44
- Sulphur atoms (S)	% wt.	0.09
Biochemical composition		
- Cellulose	% wt.	59.70
- Hemicellulose	% wt.	22.10
- Lignin	% wt.	18.20

2.2 Simulation process

In this work, the main bio-oil production and upgrading processes are developed using the Aspen Plus program V11.0. The process comprises the pretreatment of biomass feedstock, fast pyrolysis, bio-oil separation, combustion of char and pyrolysed gas, hydrotreatment of bio-oil, distillation, and hydrocracking. An overview of the plant simulation process is presented in Figure 1.

2.2.1 Pretreatment

The pretreatment operation aims to reduce the moisture content in the EFBs to decrease the heat load caused by moisture evaporation, reducing the size of the EFBs to reach the appropriate operating conditions for the proposed pyrolysis process. Due to the broad range of conditions used in many commercial studies, the designated moisture content of a dried EFB is about 10%. An EFB measuring approximately 400 μm is chosen for this study as the most suitable EFB feedstock size. An EFB in the appropriate size can reduce the heat required for the pyrolysis reactor and ash formation [6].

2.2.2 Fast pyrolysis

Pyrolysis, the key to this process, is the thermal decomposition of biomass to produce a high-quality bio-product. The most important parameters involved are pyrolysis temperature and vapor retention time. The objective of this work is to utilise bio-oil as the main product. Hence, fast pyrolysis is selected as the operating condition, with a typical temperature ranging from 450-550℃ and a retention time of around 1-5 s to provide the highest bio-oil yield [6]. However, recent studies report that the most suitable vapour retention time for fast pyrolysis to attain the highest bio-oil yield is around 1-2 s [7]. In this work, the pyrolysis process is developed following the study by [8], with the kinetic reaction models of 149 individual reactions used to convert cellulose, hemicellulose, and lignin into volatile matters (bio-oil and gas components), solid residue (char), and radical intermediates. The reaction can be categorised into five groups: primary decomposition, secondary decomposition, radical substitution, radical recombination, and char devolatilisation. The continuous stirred tank reactor (RCSTR) model is utilised to achieve fast pyrolysis in this phase since bubbling fluidised bed reactors are mostly used for fast pyrolysis. The reactor operating temperature should be varied to derive the highest bio-oil yield from the simulation.

2.2.3 Bio-oil separation

Quenching is carried out to stop the reaction state and separate the pyrolysis product. Since char acts as a vapour cracking catalyst and contributes to the formation of polycyclic aromatic hydrocarbons (PAHs) during the pyrolysis process, particularly at low temperatures, it is critical to separate it quickly and effectively. Therefore, the biochar is initially separated by a cyclone to prevent the formation of polycyclic aromatic hydrocarbons. The volatile product stream, containing several components, represents a direct mix of bio-oil, quenched down to 100°C to avoid a further pyrolysis reaction. The bio-oil is condensed using flash pyrolysis, operated at a temperature of 45°C under atmospheric pressure.

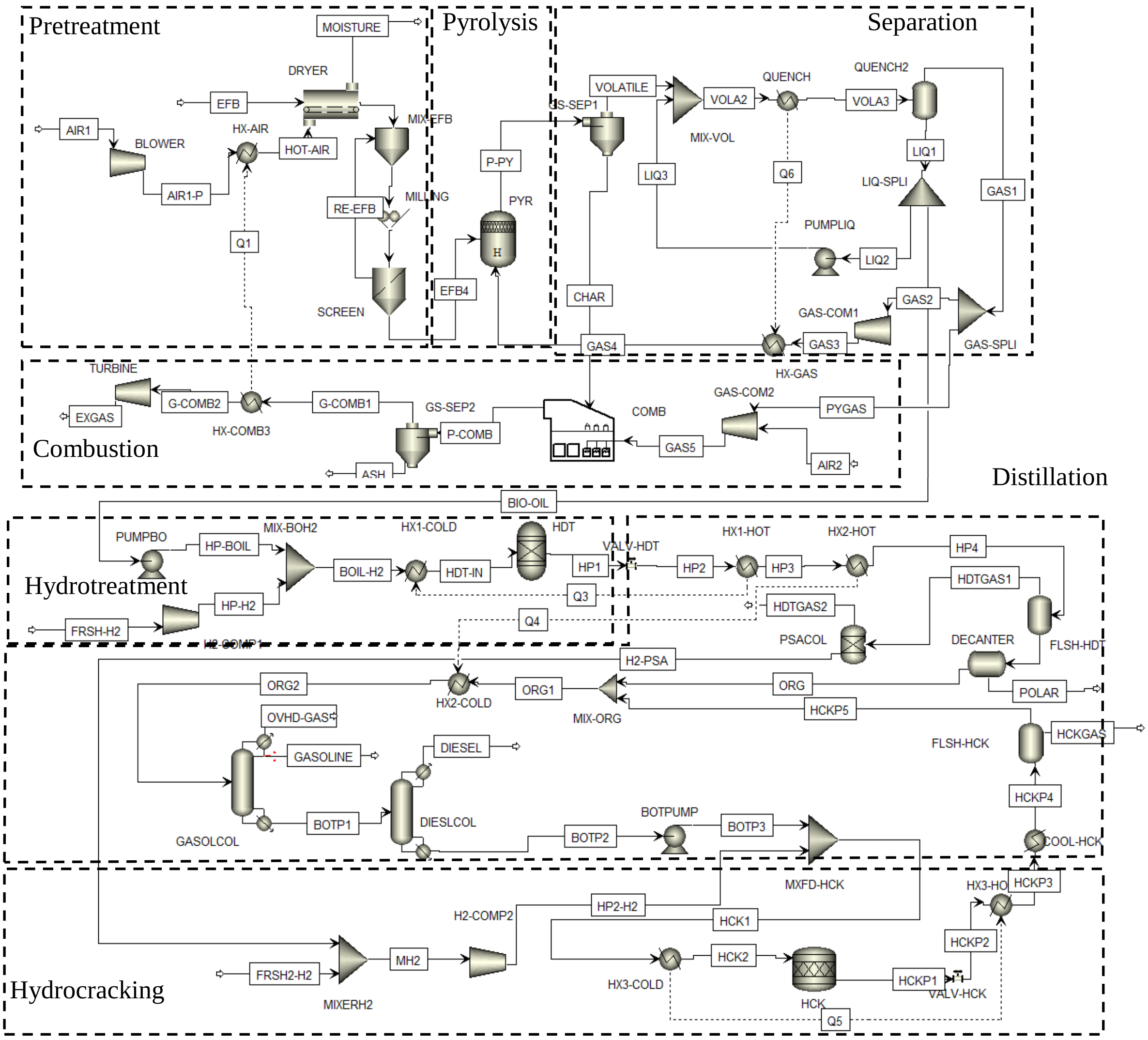

Figure 1 Bio-oil production and the upgrading process in the Aspen Plus program.

2.2.4 Combustion

The separated char is combusted with the pyrolysis gas obtained from the separation process to provide heat recovery and reduce unnecessary energy consumption. This section utilises the hierarchy combustion model, combining two reactors to accomplish actual combustion and heat generation. The first reactor performs the decomposition of the biochar by-product into the constituent compound using the yield reactor (RYields) model in Aspen Plus. The product is then fed into the second reactor to calculate the heat balance of the combustion products based on Gibbs' energy minimisation. The Gibbs reactor (RGIBBS) model is used to complete the combustion mechanism since the non-standard compound in Aspen Plus is unable to estimate the Gibbs' free energy and produce the combustion products CO_2, CO, water, O_2, N_2, and CH_4. The combustion temperature is 730℃ to entirely mitigate ash melt.

2.2.5 Hydrotreatment

Bio-oil exhibits thermal instability and poor energy density mainly due to its high oxygen content. Hence, upgrading is required. The hydrotreated yields are adjusted to provide an oxygen content of less than 2% in the bio-oil by feeding the additional hydrogen gas to elicit a reaction. Hydrotreatment is performed at an operating temperature of 387℃, a hydrogen pressure of 87 bar, and a weight hourly space velocity (WHSV) of 0.135 h^{-1}. The kinetic reaction in the hydrotreatment process is based on the previous study [9].

2.2.6 Distillation

The hydrotreated bio-oil reduces the pressure and temperature to 20 bar and 50℃ before being flashed in an adiabatic flash drum. During the gas phase, the hydrotreated gas and hydrogen are used to remove the hydrogen and light hydrocarbon compound from the hydrotreated product, thereby recovering 90% of the hydrogen for the hydrocracker. While the liquid stream is separated, the additional polar compounds from the oil product consisting mainly of water are placed in the adiabatic decanter before being subsequently transferred into distillate gasoline, diesel, and heavy residue in two distillation columns. The RadFrac model represents the two distillation columns. The first column contains gasoline and has nine stages, with the partial condenser and column pressure at 1.5 bar, while the second column is diesel and has eight stages with a total condenser and column pressure of 0.01 bar. The biodiesel acquired from the overhead stream in the second column is used as fuel in the electric power generation process.

2.2.7 Hydrocracking

As a by-product of the diesel distillation column, the bottom stream mainly comprises chrysene, which is a heavy hydrocarbon. It must be cracked down to smaller hydrocarbons within the desired boiling range to be utilised as a fuel component. In the hydrocracking process, the bottom stream is first pressurised to 90 bars to react with a fresh hydrogen stream to crack the compound. The hydrocracking reaction is developed in RStoic according to the study by [10], to obtain six reactions. The reaction takes place at 677℃ and 90 bars, further decreasing the temperature of the hydrocracked product to separate excess hydrogen gas from the cooled liquid hydrocarbon.

2.2.8 Power generation

In the case of a diesel generator, since there is no built-in model or function in the Aspen Plus software, it may be produced in another simulated model framework. The diesel engine model is developed under the assumption of calculation simplicity in the system's energy balance. In either case, since there is no open-source mathematical model for Genset, a mathematical diesel engine is created instead, and the energy equation is utilised following the work of [11]. The efficiency of mechanical-to-electrical power transfer is presumed to be 95% to complete the Genset method. Calculating the diesel engine's energy balance utilises some of the actual Genset machines to ensure the geometry and operating conditions accord with the engine specifications. Table 2 shows the 100 kW diesel generator specification. In this project, the diesel engine generator is developed using the Simulink program.

Table 2 Specification of the 100 kW diesel engine.

Specification	Unit	Value
Engine speed	round/min	1,800
Engine power output at rpm	kW	100
Total displacement	Litre	5.9
Number of cylinders		6-inline
Bore x stroke	mm x mm	102 x 120
Compression ratio		17.3:1
Max. fuel consumption	L/hr	30.7

3. Results and discussion

3.1 EFB pyrolysis products

Aspen Plus V.11 is used to simulate the EFB fast pyrolysis process. The highest bio-oil yield from the simulation is achieved by varying the temperature. The pyrolysis product yields with different temperatures are presented in Figure 2. The bio-oil yield is around 57-74% at a typical temperature range of 400-560℃. A pyrolysis temperature of 500°C obtains the maximum bio-oil yield of 74.5%, char of 12%, and gas of 13.5%. The highest char yield is obtained at a low temperature and reduces with a temperature rise. On the other hand, the gas yield increases with a temperature rise. Since the maximum bio-oil yield is required, the fast pyrolysis reactor is operated at 500°C in this study.

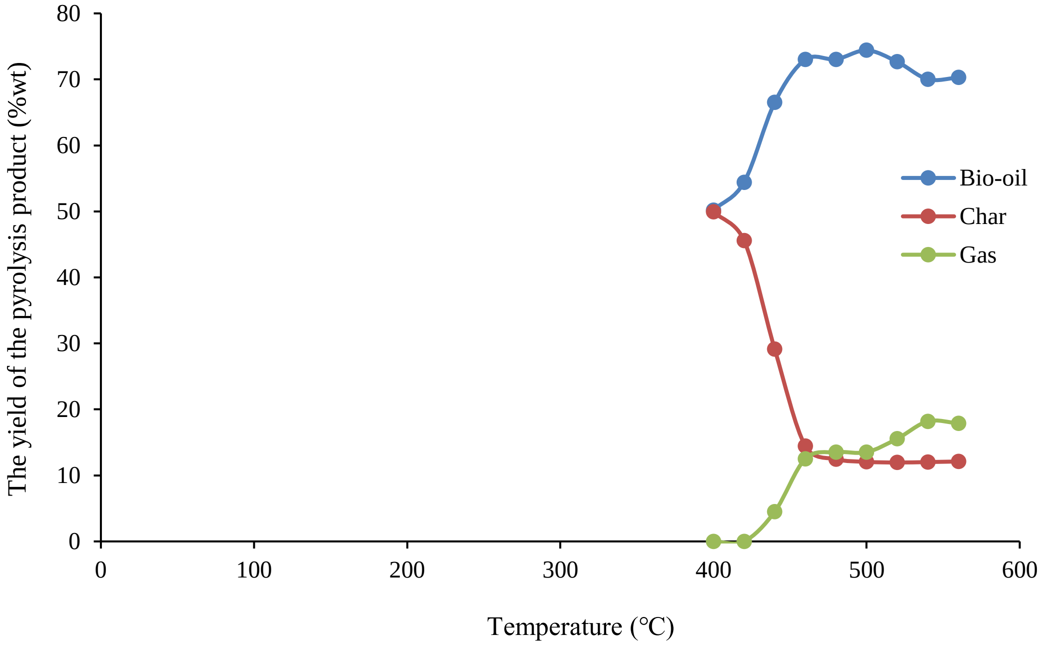

Figure 2 Bio-oil yield at different pyrolysis temperatures.

The highest bio-oil yield from the pyrolysis process is achieved at a temperature of 500℃ and a vapour residence time of 1.02 seconds. The results of fast pyrolysis shown in Tables 3 and 4 are compared to the work of [6], who experimented using the same technology. Fast pyrolysis is suitable for bio-oil production since it provides a higher bio-oil yield than slow and intermediate pyrolysis. The final products from the gasoline and diesel distillation column consist of many components. The group of final fuel compositions obtained from the bio-oil upgrading for the EFB feedstock is given in Table 5. Both fractions contain close to 80% of non-aromatic hydrocarbon plus a significant share of aromatics. They fulfil the gasoline and diesel fuel specifications and hence can be considered suitable as drop-in fuels for the power generation of vehicle and diesel engines. In comparison, the bio-oil upgrading products used for improving bio-oil into gasoline and biodiesel are presented in Table 6. Although the bio-oil yield is higher than the 2.07% obtained in the experimental study, the overall yield of the final products remains close to the experimental data contained in the work of [12].

Table 3 Comparison between the pyrolysis products from the proposed bio-oil production process in this work and the experiment performed by Abdullah and Sulaiman [6].

Products from the bio-oil production process	Pyrolysis yield (%)	
	This work	Abdullah and Sulaiman [6]
Gas	13.50	14.70
Bio-oil	74.43	72.36
Char	12.05	10.76

Table 4 Comparison between the proposed atomic composition of bio-oil in this work and the experiment performed by Abdullah and Sulaiman [6].

Elements	Atomic composition of bio-oil (%)	
	This work	Abdullah and Sulaiman [6]
Carbon atoms (C)	39.74	41.86
Hydrogen atoms (H)	7.42	7.82
Oxygen atoms (O)	52.84	50.2
Nitrogen atoms (N)	0	0.1

Table 5 Results of the final fuel product for upgrading bio-oil from simulation.

Functional group		Gasoline (% wt.)	Diesel (% wt.)
Paraffines and Naphthenes		80.74	77.27
	Paraffins/Alkanes	23.99	48.19
	Naphthenes	56.75	14.15
	Polynaphthenes	0.00	14.93
Aromatics		9.34	20.34
	Monoaromatics	9.34	5.88
	Diaromatics	0.00	0.21
	Polyaromatics	0.00	14.25
Oxygenates		8.06	2.39
	Furans	6.26	0.32
	Alcohols	1.75	1.06
	Phenols	0.06	1.01
Water		1.31	0.00
Others	Impurities (mainly CO_2)	0.54	0.00

Table 6 Comparison between gasoline and diesel products from the proposed bio-oil upgrading process in this work and other experimental studies.

Product	Unit	This work	Jones et al. [12]	Wright et al. [13]
Gasoline	kg/kg bio-oil	0.19	0.18	0.21
Diesel	kg/kg bio-oil	0.25	0.25	0.21

3.2 Economic evaluation

The Aspen Process Economic Analyzer (APEA) V11.0 is used in this study to evaluate the total cost of the equipment purchased ($7,445,900). Capital expenditure (CAPEX) and operating expenditure (OPEX) are calculated based on the equipment purchased, raw material cost, labour cost, and utility cost, following the guidelines set out in Plant Design and Economics for Chemical Engineers. From the income perspective, three profitable products are produced: gasoline, biodiesel, and electricity. All parameters used to calculate the capital budget are based on the MACRS depreciation method and a plant lifetime of 20 years. Figure 3 illustrates the capital cost distribution for each process. It can be observed that the hydrotreatment process is responsible for the highest capital cost, followed by hydrocracking and distillation. The hydrotreatment and hydrocracking processes both operate at high temperatures and high pressure, resulting in very high production costs. Whereas the distillation process is extremely complex, nonlinear, and high order. Many constraints are encountered during the production process. Equipment with unique operating characteristics inevitably involves high construction costs. Notably, the bio-oil upgrading process, comprising hydrotreatment, distillation, and hydrocracking, is responsible for 61% of the total capital costs. In comparison, the bio-oil upgrading process in [14] represents 62.5% of the total cost. The pyrolysis process is expensive due to the high operating temperature required. The overall capital cost of this plant model is USD36.26 M.

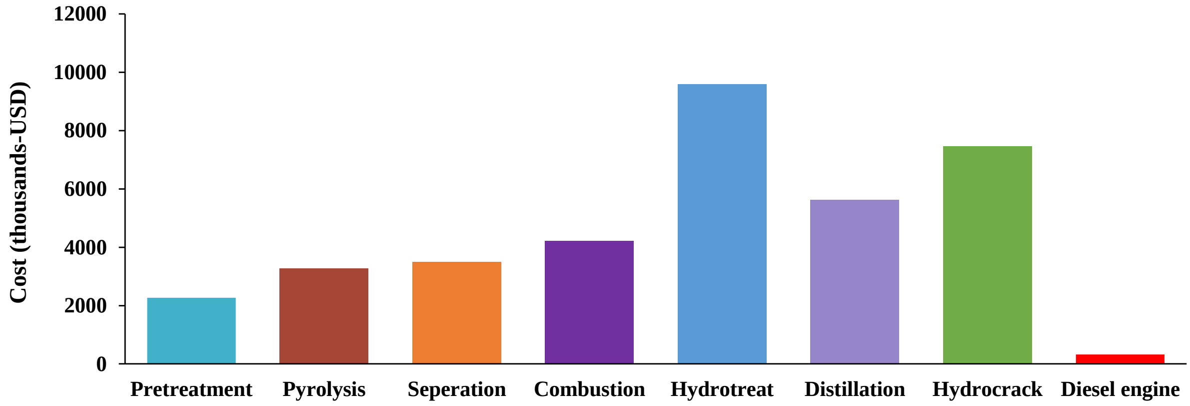

Figure 3 Capital cost distribution based on individual processes.

Figure 4 illustrates the operating cost distribution in this work and introduces important impact parameters. It can be observed that raw material represents the highest proportion of annual operating expenditure (OPEX) followed by labour cost and utility cost, respectively. This is due to the large amount of hydrogen gas required for the hydrotreatment and hydrocracking processes. The labour cost is the second-largest expenditure since the various operating procedures within the biodiesel power plant require a large number of workers, some of whom hold specific technical positions. Utility is the third-largest expenditure because it relates to direct manufacturing costs and production capacity. From the income generation perspective, the selling price of the product is shown in Table 7. The products resulting from this process are gasoline, diesel, and electricity. The gasoline product is directly used to calculate the gasoline income, while part of the diesel product is used to power diesel engines with the remainder sold as transport fuel for diesel engines. The electricity in this process is generated from diesel engines and combustion turbines.

Table 7 Product price.

Product item	Value
Gasoline	0.900 USD/L
Diesel	0.880 USD/L
Electricity	0.124 USD/kWh

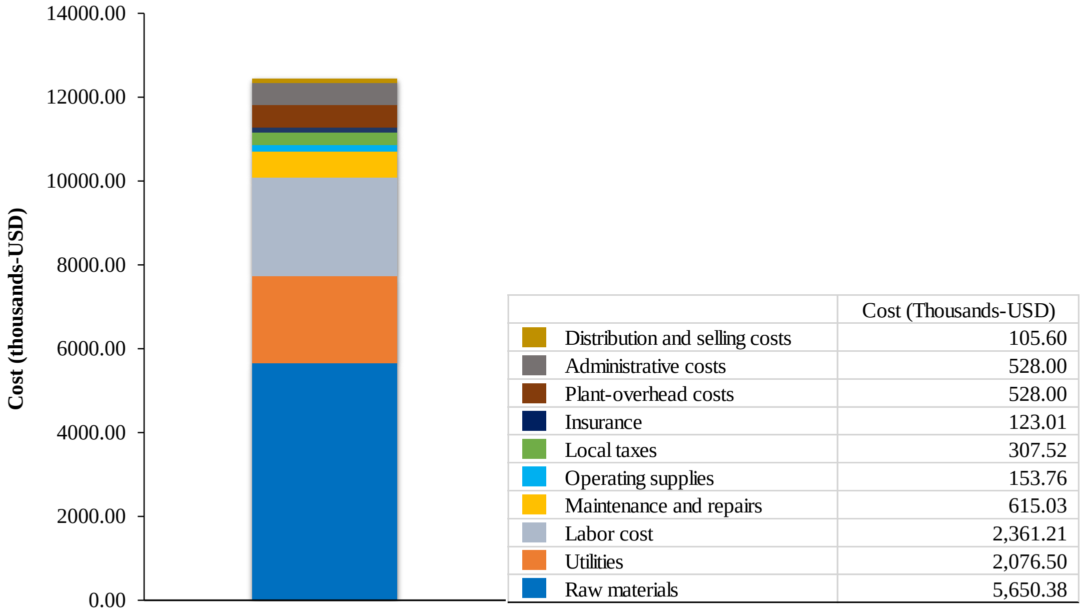

Figure 4 Operating cost distribution.

An economic analysis of this biodiesel power plant is presented in Table 8. According to the results, the biodiesel process is a worthwhile investment since the net present value is positive. The internal rate of return is greater than the weighted average cost of capital (WACC) set at 7% for economic evaluation.

Table 8 Economic evaluation results.

Parameter	Value
CAPEX	USD36.26 M
OPEX	USD10.56 M/yr
Total income	USD15.26 M/yr
Net present value (NPV)	USD10.71 M
Internal rate of return (IRR)	10.4%
Payback period (PBP)	13.18 yrs

3.3 Environmental impact

All the exhaust streams and energy consumption throughout the plant simulation are applied to determine the environmental impact. The fine particulate matter formulated from the process yielded 19.6 tons of PM2.5 eq/year. At the same time, the CO_2 emissions, which impact climate change in the case of non-managed disposal, direct combustion, and EFB fast pyrolysis, are presented in Figure 5. This process is environmentally friendly since it can reduce 69,964 and 10,446 tons of CO_2 emissions eq/year compared to landfill and direct EFB combustion, respectively [15].

Moreover, at the endpoint level, the impact category which causes damage to human health and ecosystem diversity, calculated from ReCiPe [15], is due to an increase in the global mean temperature, potentially from gas, the results of which are shown in Table 9. According to the results, the proposed process has less impact on climate change than landfill and direct EFB combustion.

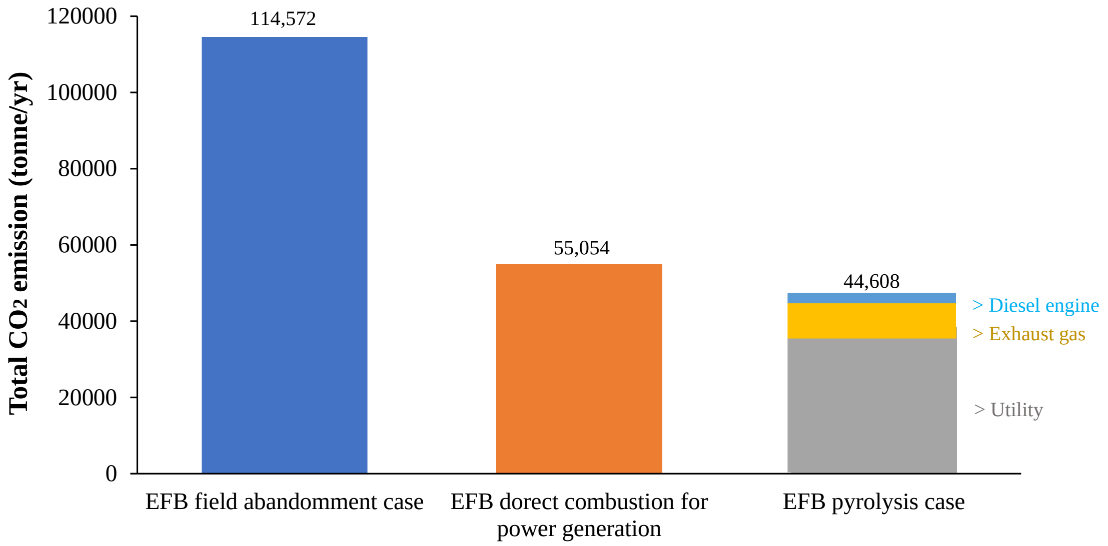

Figure 5 Climate change comparison between EFB pyrolysis and other cases.

Table 9 Climate change environmental impact assessment on EFB pyrolysis and other cases.

Parameter	EFB field abandonment	Direct EFB combustion	EFB pyrolysis
Human health (yrs)	0.2913	0.1400	0.1134
Terrestrial ecosystems (species)	0.3208	0.1542	0.1249
Freshwater ecosystems (species)	8.76E-06	4.21E-06	3.41E-06

4. Conclusion

The pyrolysis process in this study which uses 100 tons/day of EFBs (dried basis) results in an NPV, IRR, and PBP of USD10.71 M, 10.4%, and 13.18 years, respectively. The process mitigates the environmental impact by reducing CO_2 emissions from EFB landfills by around 69,964 tons of CO_2 eq/year and produces a valuable product. At the same time, damage to human health and ecosystem diversity due to climate change equates to about 0.11 years loss of life and 0.125 species annually. In both cases, the damage caused by this process is lower than landfill and direct EFB combustion. This work can enhance energy conservation by up to 100 kWatt.

5. Acknowledgements

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6. Conflicts of interest

The authors declare that they have no conflict of interest.

7. References

[1] Krungsri Research Industry. Industry Outlook 2020-2022: Palm Oil Industry [Internet]. https://www.krungsri.com/en/research/industry/; 2020 [Accessed 27 January 2021].

[2] Adams P, Bridgwater T, Lea-Langton A, Ross A, Watson I. Biomass Conversion Technologies. In: Patricia T, Paul A, editors. Greenhouse Gas Balances of Bioenergy Systems, Academic Press; 2018, p. 107-139.

[3] Dinesh M, Charles U, Pittman J, Philip H. Pyrolysis of wood/biomass for bio-oil: a critical review. Energ Fuel. 2006;20:848-889.

[4] Chiaramonti D, Oasmaa A, Solantausta Y. Power generation using fast pyrolysis liquids from biomass. Renew Sust Energ Rev. 2007;11:1056-1108.

[5] Kerdsuwan, S, Laohalidanond K. Renewable energy from palm oil empty fruit bunch. Renew Energ: Trends and Applications. 2011;6:123-150.

[6] Abdullah N, Sulaiman F. The properties of the washed empty fruit bunches of oil palm. J Phys Sci. 2013;24:117-120.

[7] Ali N, Saleem M, Shahzad K, Hussain S, Chughtai A. Effect of operating parameters on production of bio-oil from fast pyrolysis of maize stalk in bubbling fluidized bed reactor. Pol J Chem Technol. 2016;18: 88-96.

[8] Peters J, Banks S, Bridgwater A, Dufour J. A kinetic reaction model for biomass pyrolysis processes in Aspen Plus. Appl Energy. 2017;188:595-603.

[9] Luo Y, Guda V, Steele P, Wan G. Hydrodeoxygenation of oxidized and hydrotreated bio-oils to hydrocarbons in a fixed-bed continuous reactor. Bioresources. 2016;11:4415-4431.

[10] Sadhukhan J, Siew NK. Economic and European Union environmental sustainability criteria assessment of bio-oil-based biofuel systems: refinery integration cases. Ind Eng Chem Res. 2011;50:6794–6808.

[11] Vathakit K. A study of boost pressure on efficiency of an agricultural single cylinder diesel engine – theory and calculations. In: The 13th Thai Society Agricultural Engineering; 2012 Apr 4-5; Chiang Mai province; 2012. p. 191-200.

[12] Jones SB, Valkenburg C, Walton CW, Elliott DC, Holladay JE, Stevens DJ, et al. Production of gasoline and diesel from biomass via fast pyrolysis, hydrotreating and hydrocracking: a design case. Richland (WA): USDOE; 2009.

[13] Wright M, Daugaard M, Satrio DE, Brown RC. Techno-economic analysis of biomass fast pyrolysis to transportation fuels. Fuel. 2010;89:2–10.

[14] Mobolaji B, Shemfe SG, Panneerselvam R. Techno-economic performance analysis of biofuel production and miniature electric power generation from fast biomass pyrolysis and bio-oil upgrading. Fuel. 2015;143:361-372

[15] Huijbregts M, Steinmann Z, Elshout P, Stam G, Verones F, Vieira M. ReCiPe2016: a harmonized life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess. 2016;22:138-147.