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Research article

Application of teaching-learning-based optimization algorithm in designing 100 kW power plant using pyrolysis of oil palm empty fruit bunches

Chayangkul Janta-in[a, †], Kitti Wiriyalapsakul[b, †], Thongchai Rohitatisha Srinophakun[c,*]

[a] *Interdisciplinary of Sustainable Energy and Resources Engineering, Faculty of Engineering, Kasetsart University, Bangkok 10900, Thailand*

[b] *Chemical Engineering Practice School, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand*

[c] *Department of Chemical Engineering, Faculty of Engineering, Kasetsart University, Bangkok 10900, Thailand*

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Abstract

Importance of the work: Empty fruit bunches (EFBs) from the palm oil milling process have the potential to be used as a source of energy.

Objectives: To optimize the environmental impact and economic profitability of utilization of biofuel production from the EFB fast pyrolysis process.

Materials & Methods: The biodiesel power plant from the EFB fast pyrolysis process was modelled using the Aspen Plus program and optimized using the MATLAB program. The multi-objective teaching-learning-based optimization algorithm was used to maximize the net present value (NPV) while minimizing the CO_2 emission of a biodiesel power plant in each case.

Results: The optimization results showed that the best case from the economic aspect was an NPV of USD million 14.233 with 59,755 t CO_2/yr, while the best case in terms of minimizing environmental impact was with the lowest CO_2 emission equivalent of 58,770 t CO_2/yr and an NPV of USD million 12.008. The difference between these two scenarios regarding the CO_2 emission was slight (1.65%), while for the NPV, it was high (15.63%).

Main finding: Both cases produced higher CO_2 emissions than from direct combustion. However, they were still environmentally friendly since they reduced the CO_2 emission equivalent compared to using the EFB as landfill and produced valuable products, while enhancing energy conservation by up to 100 kW.

† Equal contribution.

* Corresponding author.
E-mail address: fengtcs@hotmail.com (T.R. Srinophakun)

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Introduction

Thailand is an agricultural country that produces an enormous number of agricultural products, with one of the major crop wastes being oil palm empty fruit bunches (EFBs). In 2019, the Office of Agricultural Economics reported the available oil palm product to approximately 16.8 million t, consisting of approximately 23–25% EFBs (Kritsada, 2019). Generally, EFBs, as agricultural waste, have been used for either organic fertilizer or to produce electricity. EFB, which is a raw material, is a type of lignocellulose biomass that contains cellulose, hemicellulose and lignin. These major components will influence the heating value of final fuel production, with lignin having a positive linear relationship with the heating value (Mansor et al., 2019). Most of the biomass power plants in Thailand use the direct combustion process (Barz and Delivand, 2011). This kind of power system is not environmentally suitable due to its higher particulate emissions (Riva et al., 2011). Most mitigation technologies that specifically deal with this type of direct combustion emission are still under development (Lim et al., 2015). Therefore, to efficiently produce power electricity, bio-oil production is required as a suitable source of fuel feedstock. One promising conversion process for biofuel is fast pyrolysis (Pattiya et al., 2006). Fast pyrolysis is a thermochemical decomposition process that converts biomass into biofuel based on carbonaceous residues called 'biochar', non-condensable gas and bio-liquid fuel called "Bio-oil" (Adams et al., 2018). However, Bio-oil is not considered to be of good quality because it contains high levels of sulfur and oxygen, which result in a lower heating value and a product which cannot be used in regular combustion engines (Zheng and Wei, 2011). Hence, the bio-oil upgrading process, which consists of hydrotreating and hydrocracking, was developed, in this sense, to upgrade the quality of the bio-oil into biodiesel as a competitive biofuel for diesel generators, while enhancing energy conservation by up to 100 kW to service the process system.

The current work aimed to develop a process simulation model of bio-oil production from EFBs and the bio-oil upgrading process using the Aspen Plus V.11.0 software. However, process optimization was studied to extend the analysis of the model of the biodiesel production plant. In addition to optimizing the operating and designing parameters regarding generating biofuel production, the financial-economic factors were also considered regarding profitability. While there are many criteria to determine whether a financial investment project will be profitable (Peters et al., 2002), the chosen and widely used evaluation criterion is the net present value (NPV). In addition, the environmental impact was considered as an important factor based on the CO_2 equivalent index, a metric measure, used to compare the emissions from various global-warming gases by converting gases to the equivalent amount of CO_2 emission. Therefore, all released waste and utility usage is converted to CO_2 equivalent in trying to minimize the environmental impact. In the case of process optimization, the multi-objective teaching learning-based optimization algorithm (MO-TLBO), developed in the MATLAB software program (The Math Works, 2016) was implemented as a tool for obtaining multi-optimal design in terms of economic and environmental parameters for a fast pyrolysis process utilizing EFBs for 100 kW power generation.

Materials and Methods

Materials

The properties of EFB have been utilized in various applications as a raw material for the pyrolysis process. For example, Kerdsuwan and Laohalidanond (2011) analyzed the proximate and ultimate composition determined according to American Society for Testing and Materials (ASTM) of the EFBs collected from the palm oil mill in Chonburi, Thailand. The EFB properties are presented in Table 1. The feeding rate of EFBs in this process was fixed at 100 t/d (dried basis) to produce biodiesel and gasoline. The fluidized bed reactor was operated at 450–550 °C, 1.01 bar g. The combustor was operated at 730 °C, 1.5 bar g. The gas turbine operating conditions varied based on the gas produced from combustion.

Table 1 Proximate, ultimate, and biochemical properties of palm empty fruit bunches (air-dried) in Chonburi province, Thailand (Kerdsuwan and Laohalidanond, 2011)

Property	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	% wt.	43.80
- Hydrogen atoms	% wt.	6.20
- Oxygen atoms	% wt.	42.64
- Nitrogen atoms	% wt.	0.44
- Sulfur atoms	% wt.	0.09
- Ash	% wt.	6.30
Biochemical composition		
- Cellulose	% wt.	59.7
- Hemicellulose	% wt.	22.1
- Lignin	% wt.	18.1

% wt. = Percentage weight (dry basis)

Process simulation

In the bio-oil production and bio-oil upgrading process from EFB (Fig. 1), initially, pretreatment is required to reduce the moisture content and the size of the EFBs using a drier and miller. After the pretreatment process, the EFB has a moisture content of around 8.34% and a size of approximately 400 µm. The appropriate conditions for the EFB can reduce the heat required in the pyrolysis reactor and reduce ash formation. The pyrolysis section, which is key to this process, was developed by Peters et al. (2017) and provides kinetic reaction models for 149 individual reactions to decompose EFB into the pyrolytic product. The reactor is operated in this pyrolysis condition with a residence time of 0.5–2 s at approximately 450–550 °C. The EFB is converted to biochar, bio-oil and syngas (composed of H_2, CH_4, C_nH_m, CO, CO_2, among others) in a fluidized bed reactor. Then, the biochar is passed through a cyclone separator to prevent the formation of polycyclic aromatic hydrocarbons. The volatile product is the direct-mixed bio-oil stream and is quenched to 100 °C using a cooler to avoid further pyrolysis reaction. Then, the bio-oil is condensed at flash, operated at 45 °C and atmospheric pressure. Subsequently, the biochar and gas are fed into a combustor to provide the heat for the pyrolysis process at 730 °C. After combustion, the flue gas is sent to the cyclone separator to remove the ash. The flue gas is fed into a gas turbine to produce kinetic energy that is finally transformed into electricity (up to 100 kW). The bio-oil has thermal instability and a low energy density due mainly to its high oxygen content. Hence, an upgrading process is needed. The hydrotreated yields are adjusted to produce an oxygen content of less than 2% using high pressure hydrogen at 87 bar, weight hourly space velocity (WHSV) of 0.135/hr. The hydrotreated bio-oil is separated into the gas and polar components before using two distillation columns to produce gasoline, diesel, and heavy residue. The heavy residue in the second column is sent to the hydrocracking section and broken down into lighter product, consisting of the gasoline and diesel fractions. This involves redistillation to obtain more diesel and gasoline. The biodiesel from the process is used to generate electricity using a diesel engine developed in the Simulink

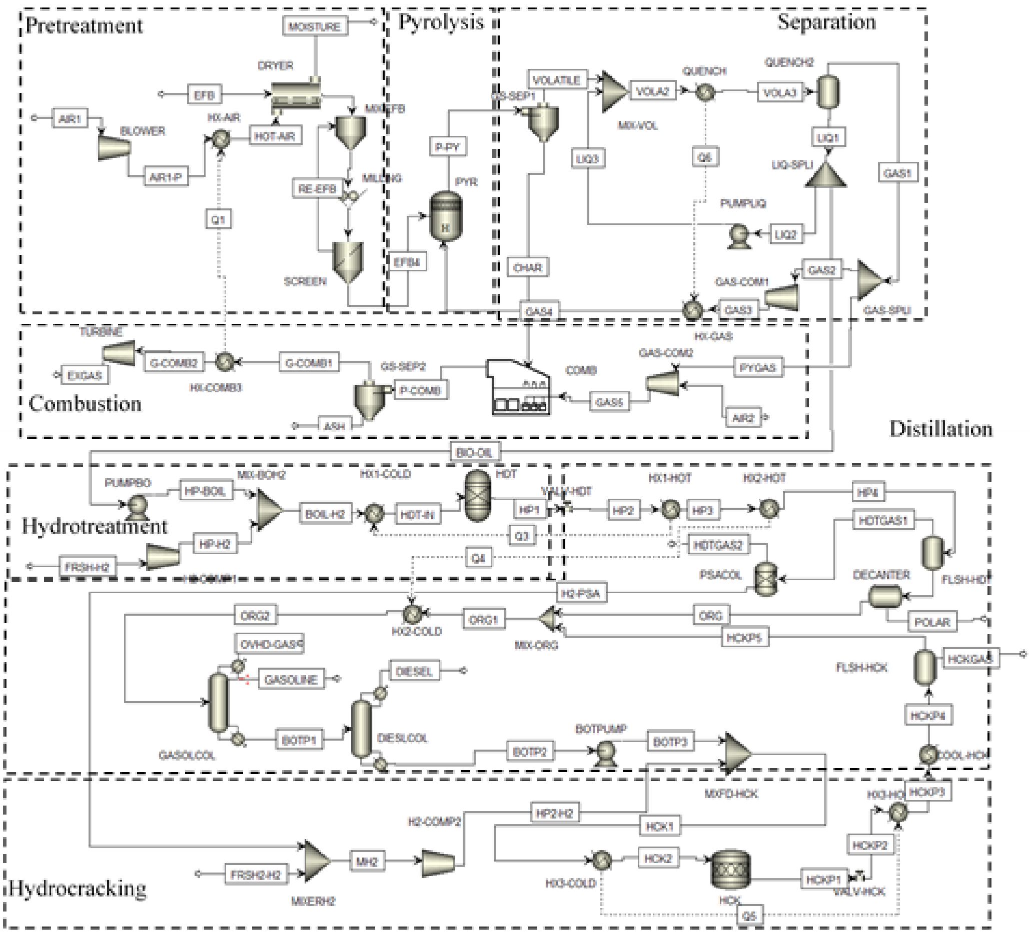

Fig. 1 Bio-oil production and upgrading process in Aspen Plus program

program which communicates with Aspen regarding dynamic actions. For diesel generators, since there is no built-in model or function created in the Aspen plus software, simulation must be run using another model platform. The assumption of the diesel engine model is used to simplify the calculation of the energy balance in the system. Because there is no open-source mathematical model for Genset, a mathematical diesel engine is developed instead, utilizing a published energy equation (Vathakit, 2012). In the Genset system, the efficiency of mechanical-to-electrical power conversion is assumed to be 95%. To calculate the energy balance of the diesel engine, some of the actual Genset machines are utilized as being representative regarding the geometry and operating conditions of the given engine specifications. Table 2 shows the specification of the diesel generator for 100kW. The details of each sub-process, data or values of all model variables are provided in the supplementary material, while the mainstream system is provided in Table 3.

Table 2 Important specifications of diesel engine utilized to supply 100 kW

Specification	Unit	Value
Engine speed	rpm	1,800
Engine power output at rated rpm	kW	100
Total displacement	L	5.9
Number of cylinders		6
Bore × Stroke	mm × mm	102 × 120
Compression ratio		17.3:1
Maximum fuel consumption	L/hr	30.7

rpm = revolutions per minute

Table 3 Main streams in Bio-oil production and upgrading process from simulation

		Stream name				
Description	Unit	P-PY	PYRGAS	BIO-OIL	GASOLINE	DIESEL
Mass Flow	kg/hr	200.0	22.4	46.8	16.4	23.3
Temperature	°C	500.0	49.9	96.4	40.0	46.2
Pressure	bar	0.8	1.0	1.0	1.5	0.0
Mass Density	kg/m^3	729.6	1.1	848.5	749.5	810.4
Average Molecular Weight		34.1	27.8	59.0	81.2	164.8
Phase:		Mixed	Gas	Liquid	Liquid	Liquid
Component Mass Flow						
WATER	kg/hr	20.5	1.5	7.7	0.2	0.0
CO2	kg/hr	35.8	6.2	0.0	0.1	0.0
CO	kg/hr	23.3	4.0	0.0	0.0	0.0
CH4	kg/hr	3.5	0.6	0.0	0.0	0.0
ETHANE	kg/hr	0.1	0.0	0.0	0.0	0.0
ETHENE	kg/hr	0.5	0.1	0.0	0.0	0.0
PROPENE	kg/hr	2.0	0.3	0.0	0.0	0.0
BUTANE	kg/hr	0.0	0.0	0.0	0.2	0.0
H2	kg/hr	2.1	0.4	0.0	0.0	0.0
ACETICAC	kg/hr	2.8	0.0	1.8	0.0	0.0
FORMICAC	kg/hr	0.5	0.0	0.2	0.0	0.0
PROPNCAC	kg/hr	0.7	0.0	0.5	0.0	0.0
PHENOL	kg/hr	0.0	0.0	0.0	0.0	0.1
PRPNYPHN	kg/hr	0.0	0.0	0.0	0.0	0.1
BENZENE	kg/hr	0.0	0.0	0.0	1.0	0.0
TOLUENE	kg/hr	0.0	0.0	0.0	0.3	0.0
M-XYLENE	kg/hr	0.0	0.0	0.0	0.1	0.2
ETYLBZNE	kg/hr	0.0	0.0	0.0	0.1	0.1
PROPBENZ	kg/hr	0.0	0.0	0.0	0.1	0.9
ACETOL	kg/hr	0.4	0.0	0.2	0.0	0.0
ACETALDY	kg/hr	17.1	2.9	0.1	0.0	0.0
GLYCOALD	kg/hr	8.9	0.0	6.0	0.0	0.0
FORMALDY	kg/hr	9.1	1.5	0.2	0.0	0.0
GLYOXAL	kg/hr	8.9	1.4	0.5	0.0	0.0
KETEN-01	kg/hr	2.4	0.4	0.0	0.0	0.0
ACETONE	kg/hr	13.5	2.2	0.2	0.0	0.0
PENTANE	kg/hr	0.0	0.0	0.0	0.5	0.0
N-HEXANE	kg/hr	0.0	0.0	0.0	1.0	0.0
N-HEPTAN	kg/hr	0.0	0.0	0.0	1.0	0.0

Table 3 Continued

		Stream name				
Description	Unit	P-PY	PYRGAS	BIO-OIL	GASOLINE	DIESEL
N-OCTANE	kg/hr	0.0	0.0	0.0	1.0	0.2
N-NONANE	kg/hr	0.0	0.0	0.0	0.1	1.2
MTYNONAN	kg/hr	0.0	0.0	0.0	0.0	1.2
UNDECAN	kg/hr	0.0	0.0	0.0	0.0	1.4
DODECAN	kg/hr	0.0	0.0	0.0	0.0	1.5
TRIDECAN	kg/h	0.0	0.0	0.0	0.0	1.3
TETDECAN	kg/hr	0.0	0.0	0.0	0.0	1.4
PENTDECA	kg/hr	0.0	0.0	0.0	0.0	1.6
OCTDECAN	kg/hr	0.0	0.0	0.0	0.0	1.5
CYCPNTAN	kg/hr	0.0	0.0	0.0	0.9	0.0
CYCHEXEN	kg/hr	0.0	0.0	0.0	1.9	0.0
CYCHEXAN	kg/hr	0.0	0.0	0.0	2.6	0.0
MTHCYCPT	kg/hr	0.0	0.0	0.0	1.8	0.0
MTCYCHXA	kg/hr	0.0	0.0	0.0	2.0	0.0
PRCYCHXA	kg/hr	0.0	0.0	0.0	0.1	2.8
BICYCHEX	kg/hr	0.0	0.0	0.0	0.0	1.8
BICYPRHX	kg/hr	0.0	0.0	0.0	0.0	1.6
NAPHTLEN	kg/hr	0.0	0.0	0.0	0.0	0.6
CHRYSENE	kg/hr	0.0	0.0	0.0	0.0	3.3
LEVOGLUC	kg/hr	29.9	0.0	20.2	0.0	0.0
HDRMTFUR	kg/hr	4.7	0.0	3.2	0.0	0.1
FURAN	kg/hr	0.0	0.0	0.0	0.3	0.0
DIMTYFUR	kg/hr	0.0	0.0	0.0	0.7	0.0
METHANOL	kg/hr	2.3	0.3	0.4	0.0	0.0
ETHANOL	kg/hr	2.8	0.4	0.2	0.1	0.0
PROPANOL	kg/hr	0.0	0.0	0.0	0.1	0.0
BUTANOL	kg/hr	0.0	0.0	0.0	0.1	0.0
HEXANOL	kg/hr	0.0	0.0	0.0	0.0	0.1
ETYLDIOL	kg/hr	0.8	0.0	0.6	0.0	0.0
CYCHXNOL	kg/hr	0.0	0.0	0.0	0.0	0.2
SINPYALC	kg/hr	1.4	0.0	0.9	0.0	0.0
CMRYLALC	kg/hr	1.9	0.0	1.1	0.0	0.0
1MGUAIAC	kg/hr	0.4	0.0	0.3	0.0	0.0
1KETDM2	kg/hr	2.2	0.0	1.5	0.0	0.0
1KETM2	kg/hr	1.6	0.0	1.1	0.0	0.0

Process simulation optimization

In process simulation optimization, when developing the EFB pyrolysis power plant using process simulation to fulfill the designated production, there is only a single set of operating conditions. The optimization technique can be used to analyze the improvement in system efficiency and can be applied by selecting many variables using a different set of directly related conditions. The plant can be improved based on optimization to achieve the best possible performance in terms of economic and environmental concerns according to the highest profit and lowest CO_2 emission. The economic and environmental analyses are based on certain key parameters resulting in a final evaluation of the competitiveness of the EFB pyrolysis power plant. However, the EFB pyrolysis power plant has a non-linear relationship between the objective of the current study and its operating condition. In the current study, the multi-objective optimization of this plant is a mixed-integer nonlinear problem and the multi-objective optimization algorithm is the multi-objective teaching-learning-based optimization algorithm (MO-TLBO) which is an optimization technique that searches for the best performance of the process (Rao et al., 2011). It is a novel optimizer inspired by the behavior of teachers and students. In this algorithm, the solutions of the population take the role of class students. By defining several learning phases, these students learn from the best solutions, and the rest of the class tries to increase their knowledge in all the subjects. Advanced optimization methods must be considered to apply this approach in the optimal design of chemical processes. Therefore, the connection between chemical processes simulation programs, such as Aspen Plus, and optimization tools, such as MATLAB, was used in this work. The MATLAB program was linked with Aspen Plus to optimize the performance of the process using the MO-TLBO algorithm, which was also developed in the MATLAB program, while Aspen Plus was used to generate the results from each set of operating conditions in the population. The calculations to determine the objective of the current study were based on the results of process simulation, namely raw material capacity (the flow rate of raw material), required utility usage, product quantity, unit operation (pressure and the temperature for each piece of equipment), unit capacity (in each piece of equipment), and CO_2 emission of the plant. furthermore, Aspen Plus included the steady-state operation constraints and product quality constraints of the process used in the optimization. The four selected decision variables were categorized into operating decision variables and design decision variables. The operating decision variables (temperature and vapor residence time of the pyrolysis reactor) mainly applied in the pyrolysis reactor part. The pyrolysis temperature range was 450–550 °C and the pyrolysis time range was 0.5–2 s, consistent with suitable operating conditions for the pyrolysis process. Both variables were continuous. The design decision variables (the stage numbers of the gasoline (8–11) and biodiesel (7–10) distillation columns) were integers. The pyrolysis temperature, vapor residence time in the reactor and the distillation stage numbers were optimized. Details on the conditions and related reactions are provided in Table S1.

Results and discussion

Process simulation results

Validation of the results based on experimental or actual results is required after the EFB pyrolysis process had been generated in the process simulation using the Aspen Plus program. The pyrolysis of EFB was the key process in this power plant. The validation of the results is necessary to confirm that the process simulation predictions can be used in other cases. The model validation compared the process simulation results of the bio-oil production process to the results from relevant experimental work. Abdullah et al. (2007) and Abdullah and Sulaiman (2013) conducted an experimental investigation on varying many operating conditions in fast pyrolysis (ash content, moisture content, temperature and the molecular size distribution of EFB feedstock. They reported that the molecular size and ash content were correlated, with the larger size of the feedstock needing to be reduced to achieve the optimum conditions for pyrolysis and to also reduce the bio-oil yield. According to the experimental results using sieved feedstock, the small particle size resulted in a higher fraction of ash content. The outcome of this experimental study provided the yield distribution of bio-oil, pyrolysis gas and biochar, as well as the composition of both the aqueous phase and the organic phase in bio-oil. In addition, they analyzed the atomic composition of bio-oil. All their bio-oil yields were higher than those obtained for the size range 300–355 μm. This indicated that not only the smallest size of the EFB particle could increase the bio-oil yield, but that it also reduced the yield due to the presence of inorganic particles. The highest bio-oil yield (72.36%) in their study was for the pyrolysis conditions of 500°C and a vapor residence time of 1.02 s, comprising and organics phase and water of approximately 61.34% and 11.02 %, respectively. Comparing the experimental results of Abdullah et al. (2007) with the bio-oil yield from the current study (approximately 74.43%), showed that the current study had a somewhat higher fraction of bio-oil. This might have been due to the simulation results that did not consider the ash content of the sieved feedstock in the simulation calculation. Furthermore, the particle size utilized in the current study was slightly larger than in Abdullah et al. (2007). The current simulation results based on the EFB data and the operating conditions as mentioned are shown in Table 4.

Table 4 shows that the yields of bio-oil and biochar from the simulation were higher than the yields from the experiment. In comparison, the yield of biochar from the simulation was lower than the result from the experiment (data not shown). However, the results show that the overall pyrolysis yields obtained from the simulation results were close to the experimental yields of Abdullah et al. (2007), with the absolute error of each product yield being less than 3%. The comparison of the atomic composition of the bio-oil in the current work was compared with Abdullah et al. (2007) and the results are shown in Table 5.

Table 4 Comparison of pyrolysis products from bio-oil production process from Abdullah et al. (2007) with current experimental data

Product from bio-oil production process	Pyrolysis yield (%)		
	Abdullah et al. (2007)	Experiment	Error
Gas	13.50	14.70	1.2
Bio-oil	74.43	72.36	2.07
Biochar	12.05	10.76	1.29

Table 5 Comparison of atomic composition of bio-oil from Abdullah et al. (2007) with current experimental data

Element	Atomic composition of bio-oil (%)		
	Abdullah et al. (2007)	Experiment	Error
Carbon	40.01	41.86	1.85
Hydrogen	7.28	7.82	0.54
Oxygen	51.84	50.2	1.64
Nitrogen	0	0.1	0.1

Table 5 shows there were some differences for the carbon and oxygen atoms in the bio-oil between the simulation and experimental results. However, the overall percentage of each element in bio-oil was rather close to the ultimate analysis of the liquid products from the experiment. The overall difference was considered acceptable. Thus, it was concluded that the bio-oil production process modeled using Aspen Plus obtained from Peters et al. (2017) could predict EFB pyrolysis very well. Therefore, the model could be used to pyrolysis products using other conditions.

Since the actual process might not be fully represented in the study by Abdullah et al. (2007), part of the bio-oil upgrading process needed to be verified by comparing with relevant work. Jones et al. (2009) reported the final products from bio-oil after hydrotreating, hydrocracking and product separation into gasoline and diesel fuel blend stocks. In their work, the bio-oil from wood fast pyrolysis occurred in a hydrotreater. The product oil was a mixture of hydrocarbons with a low level (approximately 2%) of oxygen. The hydrotreated oil was stabilized by removing the butane and lighter components using a light removal column. Then, the stable oil stream was separated into light and heavy fractions. The heavy fraction (which boils above 350 °C) was sent to the hydrocracker to completely convert the oil to gasoline and diesel blend components. The product was a mixture of liquids spanning the gasoline and diesel range and some byproduct gas. The gasoline and diesel range products were separated using distillation and these products were then suitable for blending into finished fuel (Jones et al., 2009). The comparison of the gasoline and biodiesel product is shown in Table 6.

According to Table 6, the final fuel yields of the biorefinery in the current work were 0.19 kg gasoline and 0.24 kg diesel per kg of bio-oil processed. It can see that the final fuel yields were close to those reported by Jones et al. (2009) The different results might have been due to the different feedstocks used to produce the bio-oil. However, the overall products from the bio-oil production and bio-oil upgrading processes were validated; thus, the current work is suitable for estimating EFB pyrolysis process results.

Table 6 Comparison of bio-oil upgrading products from the current work with Jones et al. (2009) as reference data

Products	Current work	Reference data
Gasoline (kg/kg bio-oil)	0.19	0.18
Diesel (kg/kg bio-oil)	0.24	0.25

Base case study

The base case study of the EFB pyrolysis process was used to optimize the process using equipment costs. The process simulation in the Aspen Plus program was used to run the base case to obtain information for the objective function file in the MATLAB program. The base case simulation results were used to estimate the cost of equipment in the process using Aspen Process Economic Analyzer (APEA) program. The equipment cost from APEA was set as the base case for estimating the cost of equipment to calculate the capital investment cost in each case since the MATLAB program cannot directly import the equipment cost for each case. Estimating equipment costs by scaling was utilized to estimate the cost of a piece of equipment where no cost data were available for the particular operational capacity involved. The selected base case was based on the validation conditions (temperature and residence time of 500 °C and 1.02 s, respectively). The number stages of the gasoline and diesel columns were 9 and 8, respectively. The results from the base case are discussed below.

In the base case, EFB dry basis at 100 t/d feedstock provided 74.43 t or approximately 54.7 m^3 of bio-oil product per day along with pyrolysis gas and biochar of 13.50 t/d and 12.05 t/d, respectively. The bio-oil was treated to produce gasoline (20.46 m^3/d) and biodiesel (25.78 m^3/d) in the bio-oil upgrading process. The yields of the upgraded products on a volume basis were gasoline (0.374 m^3 product oil/ m^3 bio-oil oil) and biodiesel (0.471 m^3 product oil/ m^3 bio-oil oil). In terms of utility consumption, the overall process required total heating of 1.51 MW or 217.34 t/d of high-pressure stream and total cooling of 8.67 MW or 7,183.52 t/d of cooling water. The total electricity usage values for the pump, compressor and crusher were 1.84 MW. The results from the process simulation were exported to APEA to estimate the equipment cost. The total purchase equipment cost of this base case was USD 7,855,752. Capital expenditure (CAPEX) and operating expenditure (OPEX) were calculated based on equipment purchased, raw material cost, labor cost and utility cost, following the guidelines set out in Plant Design and Economics for Chemical Engineers (Peter et al., 2002). From the income perspective, three profitable products were produced: gasoline, biodiesel and electricity. All parameters used to calculate the capital budget were based on the Modified Accelerated Cost Recovery System (MACRS) depreciation method and a plant lifetime of 20 yr, with the weighted average cost of capital (WACC) set at 7% for economic evaluation. An economic analysis of this biodiesel power plant base case is presented in Table 7.

Table 7 Economic evaluation results of biodiesel power plant base case

Parameter	Value
CAPEX (USD million/yr)	39.911
OPEX (USD million/yr)	9.443
Total income (USD million/yr)	15.26
Net present value (USD million)	12.25
Internal rate of return (%)	10.73
Payback period (yr)	12.2

CAPEX = capital expenditure; OPEX = operating expenditure

In terms of environmental impact, the second objective of optimizing the consideration the least cost analysis based on the global warming potential gas generated using the biodiesel power plant based on the boundary system of gate-to-gate. The CO_2 emission equivalent was applied as an indicator of the potential global warming. In the biodiesel power plant base case, the CO_2 emission equivalent was generated from three sections: exhaust gas, utility usage and flue gas from the diesel engine. The CO_2 emissions from the exhaust gas and utility usage in the base case (provided by the Aspen Plus program) were 46,922 t CO_2 emission equivalent/yr and 10,084 t CO_2 emission equivalent/yr, respectively, while the flue gas from the diesel engine was approximately 2,234 t CO_2 emission equivalent/yr. The total annual CO_2 emission equivalent of the base case of 59,240 t was compared with another alternative EFB case using the same capacity feedstock of EFB as in the base case of the biodiesel power plant. The CO_2 emissions for these non-managed disposal and direct combustion scenarios were 114,572 t CO_2 emission equivalent/yr and 55,054 t CO_2 emission equivalent/yr, respectively. The comparison of CO_2 emissions in each case is demonstrated in Fig. 2. From the results, the CO_2 emission from the base was slightly higher than for direct combustion. However, this process was still environmentally friendly as it reduced 55,332 t CO_2 emission eq/year compared with putting the EFB in landfill. Furthermore, the pyrolysis of the oil palm empty fruit bunches produced valuable products and enhanced energy conservation up to 100 kW.

After the base case had been run, the equipment cost results from the base case were used as base costs for scaling equipment in the optimization process. The NPV and environmental impact of the base case was compared with the optimal case.

Process optimization results

The optimization of the process and its key performances correlated with economic and environmental aspects. In this work, the metaheuristic optimization of the multi-objective teaching-learning-based optimization algorithm was used to determine the optimal solution by considering the optimal solution between economic and environmental impacts. After Aspen Plus had been used to evaluate the results of the economic and environmental analysis of the base case, the MATLAB program with the MO-TLBO algorithm was linked to Aspen Plus to provide the optimization. Then, a Pareto front graph was generated after the optimization had reached the maximum number of iterations. The Pareto graph of solutions for the biodiesel power plant from EFB pyrolysis after 100 iterations is shown in Fig. 3. The design and operating parameters, along with the values of both objectives in the Pareto graph, are provided in Table 8.

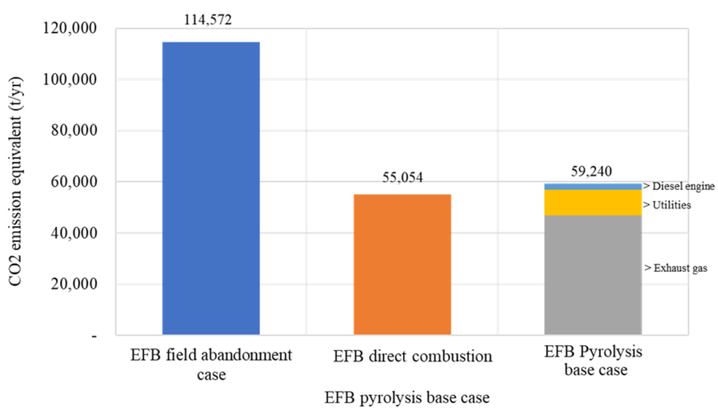

Fig. 2 Climate change comparison of oil palm empty fruit bunches (EFBs) for pyrolysis base case with other alternatives

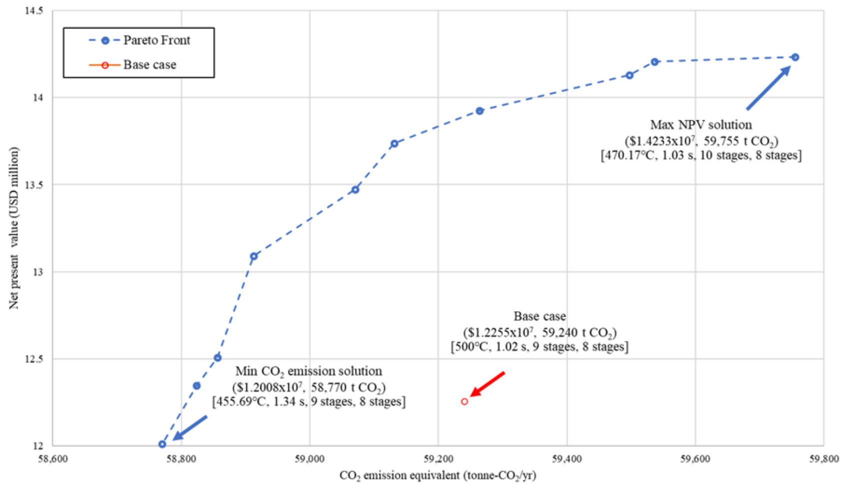

Fig. 3 Pareto set of solutions for biodiesel power plant from oil palm empty fruit bunches pyrolysis

Table 8 Comparison of design parameters between base case and optimal solutions

Case	A	B	C	D	NPV (USD)	CO_2 eq. (t/yr)
Base	500.00	1.020	9	8	12,255,000	59,240
1	470.17	1.027	10	8	14,233,000	59,755
2	469.72	1.033	10	8	14,208,000	59,536
3	467.15	1.014	10	9	14,130,000	59,497
4	465.51	1.024	10	9	13,924,000	59,264
5	462.12	1.020	10	9	13,736,000	59,131
6	462.35	1.022	10	9	13,472,000	59,070
7	458.67	1.075	10	8	13,091,000	58,912
8	456.44	1.174	10	8	12,508,000	58,856
9	455.42	1.230	9	7	12,342,000	58,823
10	455.69	1.339	9	8	12,008,000	58,770

*A = temperature (°C); B = residence time (s); C = stage number of gasoline; D = stage number of diesel; NPV = net present value

The Pareto front result indicated that the 10 points of the Pareto front were the optimal solution that was better than the base case. According to Table 8, the first case provided the highest benefit for the first objective (the highest NPV of USD million 14.233), while the case producing the lowest CO_2 emission equivalent of 58,770 t CO_2/yr (the second objective) was case 10. Increase the temperature of the pyrolysis reactor produced a higher profit due to the higher bio-oil yields. However, it required more utility consumption in the bio-oil upgrading process and produced more CO_2 emissions. Increasing the pyrolysis reaction residence time provided an advantage from the environmental aspect but had an economic penalty. Based on the design decision variables from the Pareto front results, the suitable gasoline and biodiesel distillation columns were stages 10 and 8, respectively. In addition, details of the economic and environmental factors determined in the analysis of the base case, minimum CO_2 emission case and the maximum NPV case are shown in Tables 9 and 10, respectively.

Table 8 displays the values of the main variables associated with the base case, maximum profitability and minimum environmental impact. The results showed that the CAPEX amounts in both cases (Minimum CO_2 emission and Maximum NPV) were higher than for the base case, while the OPEX amounts in both cases were lower than the base case due to decreased utility consumption. Therefore, the production costs for gasoline and biodiesel in both cases were also smaller than for the base case. The CAPEX of the minimum CO_2 emission case was higher than for the case of maximum NPV because of the large amounts of pyrolysis gas and biochar production. The capacity of the equipment in the separation and combustion section was increased, especially for the compressor and cyclone separator, which increased the costs in these sections. (See details on equipment cost in Table S2).

Table 9 Economic factors determined in analysis

Description	Base case	Minimum CO_2 emission	Maximum NPV
Gross sales (USD million/yr)	5.471	5.506	5.691
Net present value (USD million/yr)	12.255	12.008	14.233
CAPEX (USD million/yr)	39.911	40.497	40.031
OPEX (USD million/yr)	9.443	9.423	9.428
Utility cost (USD million/yr)	2.092	2.074	2.078
Production cost (USD/t gasoline)	1,684.49	1,680.32	1,660.10
Production cost (USD/t diesel)	1,190.70	1,187.78	1,173.51

CAPEX = capital expenditure; OPEX = operating expenditure.

Table 10 Environmental factors determined in analysis

CO_2 emission (t CO_2/yr)	Base case	Minimum CO_2 emission	Maximum NPV
Net CO_2 emission	59,240	58,770	59,755
Direct CO_2 emission	46,922	46,729	47,566
Indirect CO_2 emission	12,318	12,041	12,189
Compared with landfill for EFB	-55,332	-55,802	-54,817
Compared with direct combustion	+4,186	+3,716	+4,701

Regarding the environmental impacts, the results showed that both process solutions (Minimum CO_2 emission and Maximum NPV) had significant negative CO_2 emissions compared to case based on the non-managed disposal of EFBs. Although both solutions provided CO_2 emissions slightly higher than for direct combustion, both processes produced valuable products and enhanced energy conservation up to 100kW. Both solutions provided optimal process conditions, with indirect CO_2 emissions lower than for the base case. Comparing the maximum NPV design and the minimum CO_2 emission, the associated environmental impact of the maximum profitability solution was 59,755 t CO_2 eq./yr and this was an increase by 0.87% with respect to the base case solution. The optimal economic solution increased by 16.14% for the NPV compared to the base case (USD million 14.233 and USD million 12.255, respectively). The minimum environmental impact case decreased CO_2 emission by 1.65% relative to the base case (59,755 t CO_2 eq./yr and. 58,770 t CO_2 eq./yr, respectively) while NPV was reduced by 15.63% (USD million 14.233 and USD million 12.008) along the Pareto curve. Since both cases gained more benefit in terms of environmental impact compared with the case based on non-managed disposal of EFBs and produce valuable products, economic profitability was a suitable criterion on which to make a decision. The maximum NPV design with an pyrolysis reactor operating at around 470°C and a residence time of 1.027 s, along with ten and eight stages of gasoline and biodiesel distillation column, respectively, produced an NPV of USD million 14.233 and reduced the CO_2 emission by 54,817 t CO_2 eq./yr compared with the case based on EFB as landfill.

The bio-oil production process validation using the experimental data of Abdullah et al. (2007) showed that the current pyrolysis model could predict empty fruit bunch pyrolysis yields reliably. Furthermore, the bio-oil upgrading process validation (Jones et al., 2009) indicated that the overall biorefinery product could be reliably estimated and was suitable for blending into finished fuel. The simulation results indicated that a pyrolysis temperature around 450–550°C produced a high yield of bio-oil, while the yield of char was high at low temperatures and reduced as the temperature increased. On the other hand, the gas yield increased with temperature. The bio-oil yield was high during a residence time in the reactor of less than 2 s. In contrast, the yields of biochar and pyrolysis gas were low in this range, with the yields of both products increasing with the residence time. The process represented the implementation of a biodiesel power plant in the base case with the design and operating parameters established and optimized in search of its economic and environmental viability. The best economic result provided an NPV of USD million 14.233 with 59,755 t CO_2/yr, while the best case in terms of minimizing environmental impact based on the lowest CO_2 emission equivalent was 58,770 t CO_2/yr and an NPV of USD million 12.008. In both cases, the CO_2 emissions were slightly higher than for the direct combustion scenario. However, both cases were still environmentally friendly because they reduced CO_2 emission equivalent compared with the EFB landfill scenario and produced valuable products. Furthermore, they enhanced energy conservation up to 100kW, with the difference in environmental impact between the minimum CO_2 emission and the maximum NPV cases was around 1.65%, while NPV difference was around 15.63% along the Pareto curve. Thus, economic profitability was a suitable criterion for making a decision. The maximum NPV was achieved by operating the pyrolysis reactor of around 470°C with a residence time of 1.027 s, along with ten stages and eight stages of gasoline and biodiesel distillation column, respectively.

Recommendations

This work proposed process simulation and process optimization approaches that could be further developed and modified in many ways. The following ideas provide some examples for further development.

In the process simulation model, the hot and cold streams were paired by considering only the minimum temperature approach between the two streams; however, the pair of the hot and cold streams could be changed to minimize the utility cost and the capital cost of the heat exchanger in the heat exchanger network.

Each equipment cost equation model should be used in the economic objective function instead of scaling estimates from base cost. This would produce a more accurate estimate. Another important economic aspect is the evaluation of CAPEX items. A standard evaluation of CAPEX that is specific to Thailand should be better for economic analysis. Since this study utilized the standard evaluation from a chemical engineering textbook, the CAPEX items were based on global averages that might be higher than those applicable in Thailand.

Inherent safety should be another objective in process optimization, by measuring the hazard potential of the initial design in terms of fires and explosion damage and toxicity damage indices, since the process involves chemical reactions and flammable chemical components.

In conclusion, future biodiesel power plants utilizing empty fruit bunch pyrolysis simulation models could be more flexible and optimal conditions could be solved more efficiently using process simulation optimization.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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