



Research article

Experimental-based design of oil palm trunk valorization as feed to bioethanol-biochar coproduction process and its exergy-enviro-economic assessment

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Abstract

Importance of the work: Managing the very large volume of palm trunks in land clearing and the replanting of palm oil plantations is a costly and difficult. Finding a productive and environmentally friendly way to utilize this biomass is therefore important.

Objectives: To design and simulated the valorization of palm trunk as raw materials for producing ethanol and biochar in a self-sustained process.

Methods: The process simulation started by separating the trunk sap and the trunk fiber. The trunk sap was fermented to produce bioethanol. The fiber was treated by amylase hydrolysis and fermentation to convert its starch into ethanol. The remaining lignocellulosic material was sent to a pyrolysis unit for biochar production. Laboratory experiments and chemical analyses were conducted to determine palm trunk chemical composition, ethanol yield from sap fermentation and amylase hydrolysate and biochar yield. These experimental data were then used for process design and simulation.

Results: The simulation showed that when all production units operated at full capacity, the energy generated from bark combustion and pyrolysis was not enough to meet the plant's total energy demand. However, the plant model achieved self-sustained energy production by operating the amylase hydrolysis step at 63.77% capacity and sending the rest of fiber to combustion. Operating this plant using the self-sustained conditions was still economically attractive. The ethanol production cost, including plant depreciation, was USD 0.775/L (USD 0.981/kg). The return on investment was 8.36% and the payback period was 11.96 yr.

Main findings: Palm trunk valorization for ethanol and biochar production can provide an environmentally friendly and profitable solution for managing the large biomass volume generated during palm oil plantation replanting, and it is more favorable than disposal by natural decay or large-scale burning.

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Introduction

In Southeast Asia, palm oil plantations and the associated oil industries emerged in the mid-1970s. At that early stage, the only strategy for increasing palm oil production was by expanding the plantation area. Currently, such a strategy is no longer appropriate due to suitable area constraints and environmental concerns among the oil-importing countries. Thus, palm oil industries were required to improve production capacity based on intensification. Replanting is a reasonable option to maintain productivity, especially in plantations that have been in use for over 25 yr. However, the associated replanting and land clearing require large amounts of capital expenditure. Consequently, the palm oil plantation industries under pressure looked to cheaper options, sometimes neglecting the resultant environmental impact. Thus, innovation was required to create a self-financing replantation program based on increasing the value of the otherwise unused oil palm trunk waste.

The main component of dried oil palm trunks is lignocellulose which is a potential raw material for producing second generation bioethanol. Many studies have been published on utilizing lignocellulose residue as bioethanol raw material, such as cocoa pod shell (Sheta et al., 2018), cassava peel (Kongkiattikajorn et al., 2011), sugarcane bagasse pith (Sritrakul et al., 2017), coconut husk (Vaithanomsat et al., 2011) and residue from a commercial agar extraction plant (Bardant et al., 2021).

Utilization of lignocellulose oil palm trunk fiber as raw material for ethanol has been adopted in several studies, with the main objective of reducing the production cost. Those previous studies covered most of steps in second generation ethanol production. For example, Tareen et al. (2021) and Noppawan et al. (2022) modified the pretreatment step and utilized a cheap nitrogen source in the fermentation process. In addition, Sultan et al. (2022) investigated the best fiber particle size in the saccharification process to enhance ethanol production and concentration in the fermentation broth. Thanapimmetha et al. (2023) evaluated strategies for conducting saccharification and fermentation, concluding that delayed simultaneous saccharification and fermentation was the best strategy.

Hemicellulose is not the main component of dried oil palm trunks; however, it does potential economic value as raw material for producing xylitol, which has a higher selling price than bioethanol and can be produced by fermenting oil palm

hydrolysate using *Candida magnolia* TISTR 5664 (Pumiputa et al., 2008).

Scientific studies are required to evaluate the degree to which these aforementioned innovations can improve the economic feasibility of the process. Such studies must show that bioethanol production plant using oil palm trunks as a raw material can be profitable and cover the expenses required for replanting. A techno-economic analysis on the utilization of oil palm trunk (OPT) and empty fruit bunch (EFB) for bioethanol production was conducted by Suwajittanont et al. (2022) using the Aspen Plus Software and not incorporating the current findings. Their analysis concluded the best payback period occurred when the OPT-to-EFB ratio was 75:25. In addition, they proposed using pervaporation rather than extractive distillation for purification, despite the higher capital investment of the former. The techno-economic analysis and potency evaluation conducted in their study was based on oil palm trunks as a dry base. This approach was considered reasonable since the main interest was the lignocellulose fibers as feed for the second-generation bioethanol production.

In contrast, in the current study, water was taken into consideration, as the oil palm trunk moisture content exceeds 60% which prevents its utilization via direct combustion like a log of wood. Separating the water from the oil palm trunk based on mechanical pressing would produce sap as a liquid with a high sugar content and a considerable amount of starch that was a main component in the trunk fiber. This sap and starch have potential as raw material to produce bioethanol. Therefore, the current study evaluated the technical and economic prospects of utilizing sap and starch in oil palm trunks as feed for first generation bioethanol production. As has been noted above, the techno-economic analysis concluded that the entire ethanol production plant required a large amount of energy. Consequently, the current study investigated using the lignocellulose fiber for biochar production instead of as bioethanol raw material. Biochar production should not only enhance the oil palm trunk economic value but also produce excess energy that could be applied to the supply energy required in the bioethanol production plant. This study designed a bioethanol-biochar coproduction plant in a self-sustained energy system. Notably, the data for the design and simulation originated from laboratory experiments using real oil palm trunk samples and was not generated from software or based on assumptions relying on related publications.

Materials and Methods

Data collection

Oil palm trunk selection, debarking and sap extraction

An oil palm trunk from Wahau, Central Kalimantan (0102.6535, N, 11650.8361, E), Indonesia was used as a model for the physical and chemical properties. Weight measurement, debarking, sap extraction and moisture content analysis were conducted within 3 d after the palm oil tree had been uprooted.

Moisture content analysis of debarked oil palm trunk and pressed cake for sap yield

A small sample of the debarked oil palm trunk was measured carefully and its initial weight was recorded. The sample was used for moisture content determination, according to AOAC 925.10 (AOAC., 2005). Then, the dried sample weight was measured and subtracted from the initial weight to determine the moisture content. The debarked oil palm trunk was chopped up and ground before sap extraction using a 360 kW screw-press to produce pressed cake as the solid residue after sap extraction. A small sample of the pressed cake was measured for its moisture content using a similar method to that applied to the debarked oil palm trunk.

Total reducing sugar content in oil palm trunk sap

The Somogyi-Nelson method was used to determine the total reducing sugar content based on Technical Report NREL/TP-510-42623 (Sluiter et.al.,2008).

Ethanol yield from oil palm trunk sap and distillation residue proximate analysis.

Fermentation experiments were conducted to determine the ethanol yield from the palm oil sap. The fermentation conditions were based on other reported studies. Urea, phosphorus and potassium salts were used as micronutrients. The amount of each micronutrients added were 0.3% of the weight of total reducing sugar. A food grade commercial powdered yeast (Lesaffre; Indonesia), commonly used in the bakery industry, was added as inoculum at 1% of the weight of the total reducing sugar.

The initial fermentation broth was adjusted to pH 4.5–5 using 0.05 M sodium acetate buffer. Fermentation was held at room temperature (28–32°C) for 60 hr. The ethanol content in the fermentation product was determined based on its density.

The gravimetric measurements of solution densities were conducted using a densitometer (Kyoto Electronic Manufacturing; Japan). This apparatus was equipped with a weight scale, defined volume flask, autosampler and installed software which converted the measured ethanol solution sample density into an ethanol concentration as a %Volume. The apparatus's autosampler and rinsing system minimized the human error in measurement. Determining the ethanol concentration using its density is a reliable method in the ethanol industry.

For preparing samples for density measurement, the fermentation broth was diluted twice using Aquades and then distilled until the condensate reached the fermentation broth initial volume. The distillation residue was dried and sent for proximate analysis to determine its fat, protein, carbohydrate and ash contents.

Biochar yields from pressed cake

Pyrolysis experiments were conducted to determine the biochar yield from the pressed cake. The experiment was conducted in a 600 mL reactor operating at 300–400°C. The liquid product from pyrolysis was collected and weighed, as well as the biochar product. The gaseous phase was calculated based on the mass balance.

Ethanol yield from oil palm trunk starch hydrolysate

Experiments for enzymatic hydrolysis of starch content in pressed cake were conducted using amylase (Novozyme; Denmark). The amylase was diluted in 0.05 M sodium acetate buffer at pH 4.5–5. The amylase dose was 1% of the weight of the added pressed cake. Hydrolysis was conducted in a 500 mL stirred tank reactor and 75 g of dried pressed cake was added to the reactor with the aforementioned amylase solution until the total reaction system was 400 g. Hydrolysis was conducted at 80–90°C for 2 hr, after which the system was cooled to room temperature (28–32°C). Then ethanol fermentation was initialized by adding micronutrients and powder yeast in the same manner used for sap fermentation. The ethanol content was determined in a similar manner to the sap fermentation product.

Biomass component analysis and biochar yield from hydrolysis residue

The cellulose fiber residue (inert to amylase hydrolysis) was collected in the distillation residue. This fiber was separated from the residual liquid and dried. Then, the dried fiber was subjected to a pyrolysis experiment in a similar

manner to the dried pressed cake. Some of these fibers and bark samples were analyzed for their elemental components using a CHN elemental determinator (type CHN628; Lenco Corp.; USA).

Process Modeling

The process model was designed for an oil palm trunk input of 10,000 kg/d. The process commenced with debarking the oil palm trunk and ended with the ethanol and biochar storage, as shown in Fig. 1. The process consisted of six steps: 1) trunk debarking and sap extraction; 2) sap fermentation; 3) trunk starch hydrolysis and fermentation; 4) ethanol distillation; 5) pyrolysis (charcoal production); and 6) a utilities section.

The trunk was debarked and the bark was delivered to the utilities section as solid fuel. The debarked trunk was chopped and ground before sap extraction using a screw-press filter. In the screw-press filter, the ground debarked trunk was separated into sap and pressed cake, with the sap being pumped to the sap fermentation tank and the pressed cake being fed to the amylase hydrolysis process.

Sap fermentation was conducted in several parallel, stirred tanks and the fermentation process in each tank operated at room temperature for 60 hr. Micronutrient and yeast inoculum were added into these tanks. Stirring motors in these tanks ensured complete dilution of the added material and the distribution of heat.

Pressed cake, consisting of starch, lignocellulose and water, was fed to the amylase hydrolysis process. The stirred tank reactors for the amylase hydrolysis process were designed to ensure contact between the starch in the pressed cake and the amylase. Lignocellulose was considered as an inert material that did not affect the starch hydrolysis reaction. Amylase hydrolysis started by stirring the pressed cake with the amylase solution at 80–90°C for 2 hr. Then, the reaction system was cooled to room temperature, with no stirring. These tanks were also used as the fermentor for the hydrolysate. Thus, amylase hydrolysis also occurred in several parallel reactors. Then micronutrient and yeast inoculum were added to these tanks in the same manner as for the sap fermentation.

After 60 hr of fermentation, the preliminary evaporation processes were conducted in the sap fermentors and hydrolysate fermentors. The stirring and heating system of the reactor was activated to boil the fermentation broth. Direct steam injection was used for the evaporation heating system, similar to the heating system for hydrolysis. The evaporated vapor went to the condenser and evaporation terminated when the ethanol concentration in the collected condensate was 40% by volume.

The condensate tank is crucial for maintaining continuous operation in the distillation column, since the fermentation process operated in several different batches. Then, these condensates were pumped as feed into the distillation column, producing azeotrope distillate with 95% volume of an ethanol-water mixture. The residue in the amylase hydrolysate, which was mostly lignocellulose, was separated using a centrifuge unit to obtain solid residue with 40% moisture content. Then, this solid was dried and used to produce thermal energy from the biochar production process.

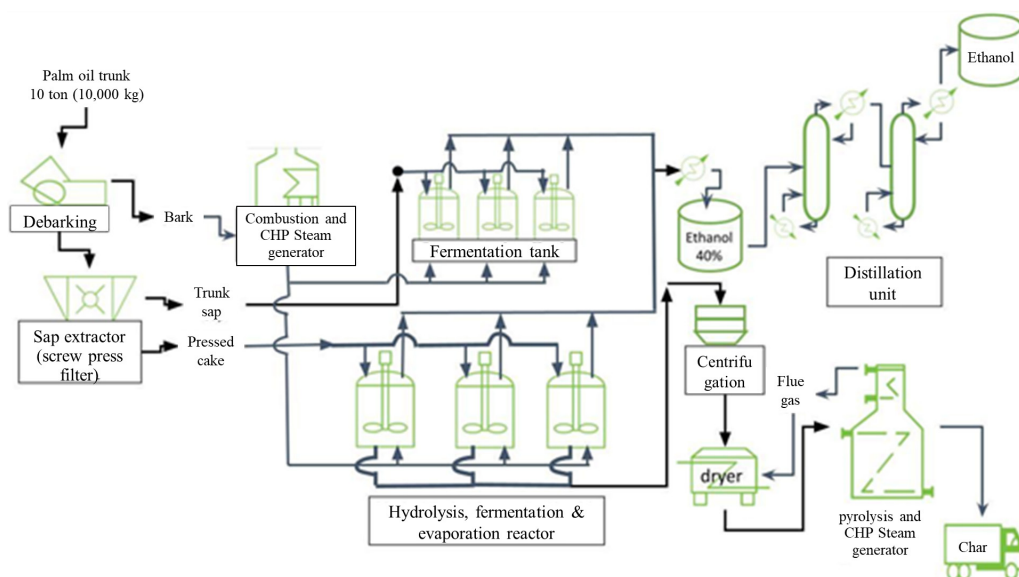


Fig. 1 Simplified bioethanol-biochar coproduction process flow diagram

The process model for the biochar production referred to the experimental study by Fauzy, et al. (2022). A continuous screw-based pyrolysis system was utilized composed of storage for the material inputs with a screw-based feeding system, a buffer material silo, a pyrolysis reactor equipped with a shaftless screw, a discharge tank, a discharge cooling screw, a biochar holding tank and a condenser, as well as a gas filtration and combustion system. The reactor was equipped with four heating zones that were monitored separately using temperature controllers; the discharge tank was also equipped with a temperature control. The pyrolysis system could be adjusted accordingly with a temperature range of 200–1,000°C. The heated areas were well insulated using ceramic fiber.

Results and Discussion

Experimental data collection

Bark and oil palm trunk overall weight

Due to the weight scale maximum load limitation, the selected oil palm trunk was chopped, debarked and weighed in parts. The overall oil palm trunk weight was the sum of weight of its parts ($1,110.5 \pm 0.25$ kg), as shown in Table 1. The bark was weighed solely to determine the portion of bark in the oil palm trunk.

Debarked trunk and pressed cake moisture content

The debarked trunk was ground and screw-pressed for sap extraction. Some sap spilled and some pressed cake stuck inside the screw-press. For more reliable data, the mass balance calculations for these mechanical treatments were conducted based on the moisture content of debarked oil palm trunks and pressed cake (75.25 ± 1.02 %w and 52.20 ± 2.12 %w, respectively). These moisture contents were average values from two measurements and the standard deviation was used to indicate measurement uncertainty.

Total reducing sugar in sap and ethanol yield from sap fermentation

According to the Somogyi-Nelson analysis, the total reducing sugar in the sap was 9.86 ± 0.22 %w. Yeast and micronutrient addition for fermentation testing were based on the measured total reducing sugar or total carbon substrate (TCS), as detailed in Table 1. The ethanol yield was 25.01 ± 2.55 %w of TCS. The theoretical yield of ethanol from glucose was 51 %w-glucose. In addition, fermentation of 10.02 %w-glucose solution with similar yeast and micronutrient addition was conducted for comparison, producing an ethanol yield of 40.5 %w-glucose, which was closer to the theoretical yield. Based on these results, the ethanol yield could be improved by ensuring all TCS in the sap was fermentable sugar.

Table 1 Parameters from experiments used for process modeling of ethanol production from oil palm trunk.

Parameter	Value	Notes
Wet weight of oil palm trunk (kg)	1110.5 ± 0.25	Value from direct weight measurement and uncertainty based on one-half of scale's smallest unit
Portion of bark (% of weight (%w))	6.01 ± 0.0025	Value from direct weight measurement and uncertainty based on one-half of scale's smallest unit.
Moisture content of debarked trunk (%w)	75.25 ± 1.02	Value from gravimetric measurement and uncertainty from deviation of repeated measurements
Moisture content of pressed cake (%w)	52.20 ± 2.12	Value from gravimetric measurement and uncertainty from deviation of repeated measurements
Total reducing sugar or total carbon substrate (TCS) in sap (%w)	9.86 ± 0.22	Value from chemical analysis and uncertainty from deviation of repeated measurements.
Ethanol yield from sap fermentation (%w of TCS)	25.01 ± 2.55	Value calculated from experimental result and uncertainty from deviation of repeated measurement
Yeast inoculum addition (%w of TCS))	1	Refer to experimental parameters
Urea addition (in %w of TCS)	0.3	Refer to experimental parameters
Phosphorus & potassium addition (%w of TCS)	0.1	Refer to experimental parameters
Dried solid substrate feed (%w of amylase solution)	18,75	Refer to experimental parameters
Amylase addition for hydrolysis (%w of pressed cake feed)	1	Refer to experimental parameters
Ethanol concentration in amylase hydrolysate fermentation (%volume)	3.77 ± 0.24	Based on gravimetric measurement and uncertainty from deviation of repeated measurement
Biochar yield from pyrolysis of pressed cake (% of feed weight)	27.1 ± 0.005	Based on gravimetric measurement and uncertainty from one-half of scale's smallest unit
Biochar yield from pyrolysis of hydrolysis residue (% of feed)	26.9 ± 0.005	Based on gravimetric measurement

Ethanol yield from fermentation of amylase hydrolysate

The dried pressed cake consisted of vascular bundle fibers (average length of 10–30 mm) and parenchyma granules (average diameter 0.5–1 mm). Mixing these substrates with amylase solution produced a slurry mixture which caused difficulties in analyzing the hydrolysate total sugar content accurately. Then, the hydrolysate was subjected directly to fermentation testing with yeast and micronutrient addition doses based on the weight of the pressed cake fed. Next, the amylase hydrolysate slurry was diluted and distilled for ethanol analyte preparation. Two fermentation tests were conducted in series at different times. The measured ethanol concentration in the amylase hydrolysate was 3.77 ± 0.24 %V as shown in Table 1. This experimental result represented any deviation to the assumption that lignocellulose is an inert material and was used for the simulation. The unhydrolyzed solid residues (mainly lignocellulose) were separated in the distillation bottom product.

Biomass component and biochar yield

The elemental component analysis of the bark and hydrolysis residue are shown in Table 2.

The higher heating value (HHV) of these biomass elements amounts was calculated using Equation 1 (Channiwalla and Parikh 2002):

$$\text{HHV} = 0,3491\text{C} + 1,1783\text{H} + 0,1005\text{S} - 0,1034\text{O} - 0,0151\text{N} - 0,0211\text{Ash} \quad (1)$$

where C, H, S, O and N are the elements carbon, hydrogen, sulfur, oxygen and nitrogen.

Both the pressed cake and the hydrolysis residue were used as feed to the pyrolysis reactor, resulting in biochar yields of 27.1 %w-biomass and 26.9 %w-biomass, respectively. These yields were used to calculate the combustion energy in the process modelling, based on Fawzy et al. (2022) that used olive pruning residue as the pyrolysis feed, with the modelling results based on mass yields of approximately 29% biochar and 71% pyrolysis gas. However, their experimental work determined mass yields of approximately 23.4 and 76.6% for the solid and gaseous fractions, respectively. The difference in the biochar yield between the experimental and simulated results was

approximately 5.6%, which was consistent with those reported in the literature (Liu et al., 2022). The difference between the biochar yield from the pressed cake and hydrolysis residue in the current study compared to the olive prune modeling was also less than 5.6%. Thus, the olive prune pyrolysis model was adopted for the current study to calculate the amount of gas produced and the energy obtained. The energy generated from pyrolysis and from the combustion of the bark and hydrolysis residue was used to supply all the plant energy requirements.

Proximate analysis results

The protein, carbohydrate, fat and ash contents in the dried fermentation residue are shown in Table 3. These data were useful for calculating the exergy of the sap fermentation residue in the process modelling. Based on the analysis of the results in the current study, the components were harmless to human safety and the environment and were readily biodegraded. Its existence in the sap fermentation broth residue as residue water did not require extra residue management systems.

Process Modelling

For the modeling input, 10,000 kg/d of oil palm trunk was fed into the process that commenced with debarking. As much as 601 kg/d of bark was delivered to the dryers to be utilized as fuel for the steam generator. Then the debarked trunk was chopped and ground before it was screw-pressed for sap extraction. Neglecting sap losses due to spillage or other minor effects, the amount of sap obtained was 4,375.16 kg/d.

The fermentation tanks require electrical energy for the motors involved in mixing and diluting the yeast and micronutrients at the start of the process, as protein and fat from the yeast cells form during the fermentation along with the ethanol product. The exergy of the fermentation residue was calculated based on the determined residue component in Table 3.

Table 3 Component analytical results of sap fermentation residue

Parameter	Value
Calorific value	315.71 kcal/100g
Calories from fat	13.59 kcal/100g
Fat	1.51 % dry weight
Protein	25.09 % dry weight
Carbohydrate (by difference)	50.44% dry weight

Table 2 Elemental component of palm oil biomass and calculated higher heating value (HHV).

Biomass sample	Elemental component (%)					Calculated HHV (MJ/kg)
	Carbon	Hydrogen	Nitrogen	Oxygen	Ash	
Hydrolysis residue	41.71	7.48	1.24	44.68	4.89	18.63
bark	42.2	3.3	0.7	44.7	6.16	13.86

Chemical exergy for each component was based on Bosch et al. (2012) and Lythcke-Jorgensen et al. (2014). The chemical exergy loss in sap fermentation was calculated as 29.16 MJ/d. The fermentation tanks were equipped with direct steam injection as the heating system for evaporation which produced additional water (598 kg) in the fermentation tanks. Thus, the sap fermentation was designed with three parallel tanks with each having a volume of 6,000 L. This system boiled the fermentation broth and the obtained vapor was removed from the tank and collected in a condenser. The ethanol concentration in the condensate was monitored and the heating halted when the concentration reached 40%V. Evaporation was the major contributor to total exergy loss in sap fermentation (up to 1,915.11 MJ).

In the experimental stages, the pressed cake was dried before the amylase hydrolysis to enable the accurate calculation of the solid substrate loading portion to the amylase solution. In the process modelling, the water content in the pressed cake fed to amylase hydrolysis was calculated as the water input to meet a similar solid substrate loading portion with the experimental conditions. The pressed cake consisted of 2,326.5 kg fiber and 2,698.34 kg water. Thus, 23.27 kg of amylase was diluted using 6,160.16 kg of acetate buffer to produce a solid substrate portion of 18.75 %w of amylase solution. An additional 1,223 kg water was provided by the condensation from the steam injection heater. Based on these figures, the hydrolysis reactor volume was set at 15,000 L and the process was designed in three parallel reactors.

Amylase hydrolysis commenced with heating to 80–90°C and stirring the reaction mixture for 2 hr. Then the cooling system replaced heating to reach room temperature (28–32°C) to initiate fermentation. The inoculum and micronutrient were added in this stage. At this point, the thermal energy required was 3,092.50 MJ and the electrical energy for the stirring and cooling pump motors was 2,053.62 MJ. Next, fermentation was conducted for 60 hr, which required no electrical or thermal energy. Fermentation was terminated by initiating steam injection to boil the fermentation broth at 110°C. This temperature was set slightly above atmospheric boiling point to provide sufficient vapor pressure to remove the vapor from the reactor. Subsequently, the vapor was collected in the condenser. The ethanol concentration in the condensate was monitored and reactor heating stopped when the concentration reached 40%V. The thermal energy required for evaporation was 5,032.39 MJ and the electrical energy required was 513.41 MJ.

The ethanol from hydrolysate fermentation and sap fermentation was stored in a condensate collecting tank to ensure continuous feeding for the distillation units. The ethanol concentration was 40%V (0.19 mole fraction). This was similar to the feed in the reference for the distillation model (Ghazi et al., 2012), where the ethanol feed was 6,529.22 kg/hr and their optimized case induced a reflux ratio of 8.61 and a distillate rate of 2,284.23 kg/hr. In the current study, the maximum 40%V-ethanol feed was only 1,007.25 kg/d.

Next, the fermentation residue in the reactor was pumped to the centrifugation unit to separate the solid content. The electrical energy required for this unit was 909.8 MJ. Then, the solid was dried and fed into the pyrolysis chamber for biochar production. Based on Fawzy et al. (2022), a considerable amount of thermal energy could be obtained by burning the volatile substance from pyrolysis at 1,000°C, producing thermal energy as gas (13.53 MJ/kg). The pyrolysis itself required energy that was supplied by burning 31.26% of the gas. The energy from the combustion of the remaining gas could be used for supplying thermal energy in other units or converted to electrical energy. It was determined that the steam power plant (450 kW electric power) required approximately 2524 kW of thermal heat.

Exergy and energy analysis

If all the solid residue from amylase hydrolysis were used, then 2,039 kg biomass with 10% moisture content was available for input to the pyrolysis unit, which required 5,466.02 MJ of thermal heat and produced 552.56 kg biochar and 1,486.42 kg of volatile substances in the gaseous phase. Combusting the gaseous phase at 1,000 °C produced more thermal energy than was required for drying the pyrolysis feed and conducting the pyrolysis reaction. The excess thermal energy from gas combustion was 11,690.80 MJ and combined with the combustion of bark, produced a total thermal energy of 18,037.08 MJ that could be supplied by the process model. The total thermal energy required by the model was 12,220.86 MJ. The required electrical energy was 5,742.37 MJ, which was equal to 32,208.32 MJ of thermal energy if the electricity were produced using an internal steam power plant. Thus, the thermal energy demand was 44,429.18 MJ, as shown in Fig. 2. There was a thermal energy deficit of 26,756.61 MJ.

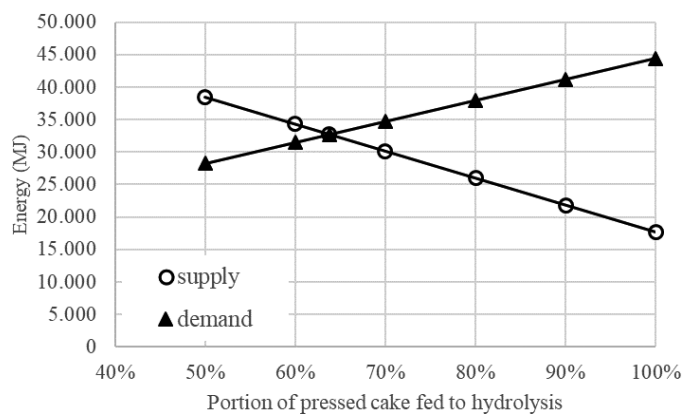


Fig. 2 Simulated energy supply and demand for bioethanol-biochar coproduction plant to amylase hydrolysis feed.

This thermal energy deficit could be supplied by liquified natural gas (LNG) combustion, with the amount required being 483.21 kg. An alternative option would be to produce energy from combusting some of the trunk fiber that was supposed to be the feed for the hydrolysis process. For this option, initially, the pressed cake was split into two parts, with 63.77%w of the pressed cake going to the amylase hydrolysis process and 36.23%w going to the Combustion and CHP steam generator together with barks. Energy from combusting 36.23%w of the pressed cake added to bark combustion, combined with the energy from the combustion in the pyrolysis gaseous phase, could supply the entire plant energy demand. In this self-sustained operating condition, the ethanol produced from 10,000 kg-wet-weight of oil palm trunk was 415.14 kg, with 154.10 kg from sap fermentation and 409.34 kg from amylase hydrolysis. The produced biochar reduced to 352.37 kg.

The total exergy loss in this model when operated using self-sustained conditions was 53,032.64 MJ. The exergy loss distribution is shown in Fig. 3. The exergy loss in the amylase hydrolysis process made up the largest portion. In addition, this process consumed the largest portion of energy in terms of thermal energy for hydrolysis and evaporation and electrical energy for slurry mixing during hydrolysis. Debarking, mechanical treatment and the centrifugal unit were grouped together as they only required electrical energy. This group was the second largest portion of exergy loss.

Environmental analysis

No additional fossil fuel was required if the model operated in the self-sustained conditions. The carbon dioxide released to the environment was mainly in the pyrolysis unit and the CHP furnace where the combustion of bark and trunk fiber occurred.

These CO₂ emissions were considered zero due to biomass combustion. In addition, carbon dioxide was released during sap and hydrolysate fermentation (Table 4). If the bioethanol-biochar coproduction plant operated at full capacity, fossil fuel would be required to supply energy. By operating in the self-sustained conditions, the plant saved 1,344.47 kg CO₂ emission for every 10,000 kg of palm oil trunk processed.

As with palm oil empty fruit bunch (EFB) residue, natural decay is a common approach for removing palm oil trunk residue in replanting programs. However, biomass residue decay should be avoided, since the process produces methane, which has a larger global warming potential (GWP) than CO₂. A previous study calculated the CO₂ equivalent emissions avoided from EFB decay by converting this biomass into bioethanol. However, the bioethanol production in that study converted the cellulose from EFB, with process yields of 11.5%w-ethanol/w-biomass. The GWP impacts, evaluated using the CML IA Baseline 2016 model, indicated 0.14 kg CO₂eq would be saved per kilogram of ethanol produced (Setiawan et al., 2024). That study was used to calculate the GWP impact reduction from the current simulated bioethanol-biochar coproduction plant. Assuming that the palm oil EFB components are similar to those for the palm oil trunk, then the GWP impact from 10,000 kg of palm oil trunk would be 1,835.09 kg lignocellulose. Thus, by not allowing palm oil trunk to decay naturally and instead feeding it into the bioethanol-biochar coproduction plant would result in a reduction of 29.55 kgCO₂eq GWP impact when considered with methane biogenic and N₂O emissions.

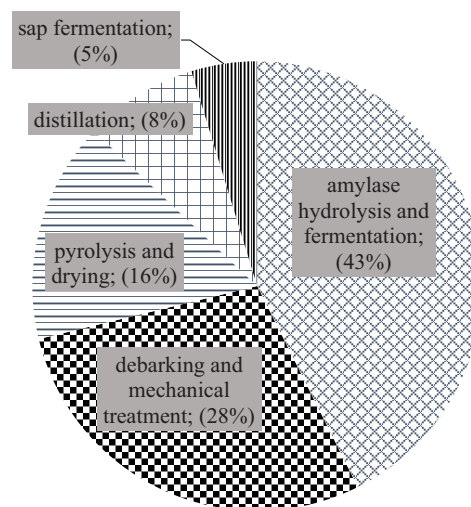


Fig. 3 Exergy loss distribution in simulated bioethanol-biochar coproduction plant when operated using self-sustained energy.

Table 4 Residue water and carbon dioxide emission from bioethanol and biochar coproduction plant with 10,000 kg/d palm trunk as feed.

Parameter (kg)	Amylase hydrolysis operating capacity	
	100%	63.77%
Product		
(1) Ethanol	563.44	415.14
(2) Biochar	552.56	352.37
Water input		
(1) Water from oil palm trunk	7,073.5	7,073.5
(2) Additional process water		
(2.1) Water injected for heating	1,821	1,377.91
(2.2) Water for formulating amylase solution	6,160.16	4,708.29
(2.3) Water from distillation residue (recycled)	(562.85)	(350.15)
Total additional process water	7,418.31	5,736.04
Residue water		
(1) In form of vapor (dryer)	1,019.49	1,118.40
(2) Sap fermentation	4,182.37	4,182.37
(3) Centrifuge	8,717.60	5,559.27
Total residue water	12,899.98	9,741.64
CO ₂ emission		
(1) Sap fermentation	85.99	85.99
(2) Hydrolysate fermentation	287.63	183.42
(3) Fossil fuel combustion (LNG)	1,344.47	0
Total CO ₂ emission	1822,01	272,53

LNG = Liquefied Natural Gas.

The water input to the process from the oil palm trunk was 7,073.5 kg or 55.22% of the total water input, which was greater than the required additional water (5,736.04 kg). This additional water was required for steam that was injected as heat and for preparing the amylase solution. The main sources of the residue water were sap fermentation residue and the centrifuge unit which separates solid residue from amylase hydrolysis and the fermentation process. Analysis of the total dissolved solids in the residue water from fermentation residue showed the components were harmless to human safety and environment and readily biodegraded. Their existence in the residue water did not require extra residue management systems.

Water from the distillation bottom residue can be recycled to the process due to its high purity. In addition, water was released to the environment as vapor from the dryer which reduced the biomass moisture content from 40% to 5%, to meet pyrolysis and furnace specifications.

Economic analysis

The total purchased equipment cost was USD 255,750 with the breakdown of equipment costs shown in Fig. 4. The price reference year was 2025 and all prices were obtained from digital market places. The total investment cost estimation for this study used relevant Lang factors, which are summarized in Table 5.

The plant was designed to operate 300 d/yr. The operational cost was calculated by neglecting the oil palm trunk price. Thus, the operational cost component was only for labor and water and the chemicals required such as amylase, yeast powder and micronutrients. In addition, any subsidies associated with the production of renewable value products were not taken into account.

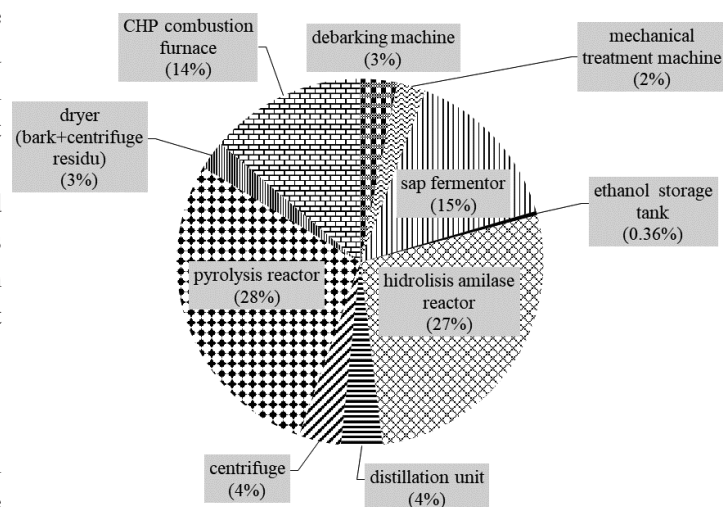


Fig. 4 Equipment cost distribution for bioethanol-biochar coproduction plant.

Table 5 Lang factors for estimating total capital investment

Cost Equipment	Lang Factor
Purchased equipment	1
Purchased equipment installation	0.39
Instrumentation and control	0.26
Piping	0.31
Electrical system	0.1
Building	0.29
Yard improvement	0.12
Direct cost (DC)	2.47
Engineering and supervision	0.32
Construction expenses	0.34
Legal expenses	0.04
Contractor's fee	0.19
Indirect Cost (IC)	0.89
Contingency	0.2 (DC + IC)
Fixed capital investment (FCI)	Cont ingency + DC + IC
Working capital (WC)	0.15 FCI
Total Investment Cost	FCI + WC

The cost of capital was 10%/yr, assuming the equipment was depreciated over 10 yr. The total annual cost was the sum of the annual operating cost and the capital cost (ACC). Since the plant was assumed to be in Indonesia, then the tax rate (t) selected for calculating ACC was 5%, see Equation 2:

$$ACC = \frac{i(1+i)^n}{1 + (1+i)^n} \quad (2)$$

The plant model was designed to operate in self-sustained conditions; thus the ethanol production rate was 415.14 kg/d or 525.49 L/d and the biochar produced was 352.37 kg/d. The ethanol production cost for this model was USD 9.81/kg or USD 0.775/L, calculated using Equation 3:

$$Production\ cost = \frac{Total\ operating\ cost}{Production\ rate} \quad (3)$$

The estimation of capital investments usually comes with uncertainty of $\pm 30\%$, while volatilities for ethanol price were considered in the $\pm 20\%$ range.

In Indonesia, the ethanol price in October 2025 for fuel substitute was USD 0.85/L. For other purposes, the price would be much higher due to liquor tax. In other regions, the approximate ethanol prices per liter were: USA USD 0.67; Brazil USD 0.80; Spain USD 2.91; France USD 0.75 (EUR 0.75) and Sweden USD 1.58. Using a selling price of USD 1/L for ethanol and USD 131/t for biochar and excluding the annualized capital cost, this model had a return on investment of 8.36 %, based on Eq. (4). The payback period was 3,588 days or 11.96 yr, as summarized in Table 6.

$$return\ on\ investment = \frac{Annual\ income}{Total\ capital\ investment} \times 100\% \quad (4)$$

Conclusion

An exergy-enviro-economic assessment was carried out based on the simulation of bioethanol and biochar co-production from oil palm trunks. This kind of assessment on up-and-coming technologies is essential to provide improved predictions on the associated expenditures and potential profits, since the investment in unproven ventures carries high risk. This simulation showed when all the process steps operated at full capacity, the bioethanol and biochar produced from 10,000 kg-wet-weight of oil palm trunk were 563.44 kg and 552.26 kg, respectively. However, in this scenario, the thermal energy from pyrolysis and bark combustion was inadequate to meet the overall plant energy requirements. This energy deficit of 28,166.6 MJ could be met by the combustion of 483.21 kg LNG. However, combusting this fossil fuel would add emissions of 1,344.47 kg of CO₂. By operating the amylase hydrolysis step at 63.77% and combusting the rest of pressed cake feed, the plant model achieved self-sustained energy, with the ethanol and biochar products reduced to 415.14 kg and 352.37 kg, respectively. These self-sustained operating conditions reduced the total process water required from 7,418.31 kg to 5,736.04 kg, leading to a reduction in the residue water from 12,899.98 kg to 9,741.64 kg. Furthermore, operating this plant using the self-sustained conditions would still be economically attractive. The ethanol production cost, including plant depreciation (ACC), was USD 0.981/kg or USD 0.775/L. Assuming an ethanol selling price of USD 1/L and a biochar selling price USD 131/t, the ROI was 8.36 %, with a payback period of 11.96 yr.

Table 6 Economic analysis output for bioethanol-biochar coproduction plant with palm trunk feed (10,000 kg/d) and bioethanol and biochar production rates of 415.14 kg and 352.37 kg, respectively.

Economic parameter	Value (USD)
Equipment cost	255,750
Total capital investment	1,185,862
Annualized capital cost	76,840
Operating cost	14,241
Total annual cost	91,082
Production cost	0.981/kg or 0.775/L
ROI	8.36%
Payback period	3,588 d or 11.96 yr

Addressing the technical limitations in this experimental-based simulation may lead to further experimentation obtaining better ethanol yields. The theoretical ethanol yield was 51%w of carbon substrate and the yield from glucose solution in similar conditions with sap fermentation reached 40.5%w of glucose. The current experimental result based on ethanol yield from sap fermentation was 25.01%w of carbon substrate. Suggested improvements to increase the ethanol yield from sap fermentation include searching for a more suitable yeast or more favorable operating conditions. Similar experimental approaches could be applied to improve the ethanol yield in the fermentation of amylase hydrolysate. Economic limitations may have resulted from the assumption that the plant would be located in Indonesia, which uses local legislation for tax expenditure, as well as the assumption that the palm oil trunk material was available at no cost. The actual economic feasibility would be less attractive if the expenses associated with these two factors increased. Dissolved solid residue in the fermentation broth was characterized as guidance in selecting a water residue management system. That characterization showed that all the components in the dissolved solid residue were harmless to the environment and biodegradable. The current simulation resulted in no lignin, nor was there a high soda content in water residue, in contrast to second-generation bioethanol technology that requires an extra residue water management system.

The economic analysis indicated that the payback period for this simulated plant was nearly 12 yr. However, the palm oil replanting program might be completed in a shorter period. Thus, further adjustment studies are required to define the appropriate plant capacity for the replanting program. This simulated plant would be more attractive if the plant capacity increased.

Finally, a bioethanol-biochar coproduction process using oil palm trunk material is an environment-friendly and profitable option to deal with the large biomass load resulting from replanting palm oil plantations. This is a much better option than relying on natural decay to manage the palm trunk residue or worse still by broadscale burning in the plantation.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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