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Techno-Economic Analysis of Ethylene Production from Empty Fruit Bunch

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Abstract. Oil palm empty fruit bunch is classified as primary lignocellulosic residue from the palm oil industry. It is considered to be a promising feedstock for bioconversion into value-added products such as bioethylene. However, using this material to produce bioethylene remains a significant challenge for small and medium enterprises. Hence, techno-economic and sensitivity analysis of bioethylene plant treating empty fruit bunch was performed in this study. The information based on extracted data was employed to develop a simulation on an industrial-scale semi-continuous production process. The production plant's process description and cost analysis with a production capacity of 100,000 kg/hr were summarized. The result based on 20 years of operation indicated that the net positive value of the plant of lower capacity was negative. However, the value increased towards the positive as the plant capacity increased. Ethylene yield of 0.16 Tonethylene/TonEFB was obtained, with a product purity of 99.3%. Economic analysis of the simulated process plant revealed that the process is highly profitable at a plant capacity rate of 100,000 kg/hr, with a payback period of 4.11 years. Negative NPV values for the first 4 years and positive for the rest life span and a profitability index of 1.11.

Keywords: Bioethylene, Lignocellulosic, Techno-economic, Empty fruit brunch, Plant, Simulation

Introduction

Ethylene is known to be one of the most important petrochemical intermediates as it is used as a feedstock for several products. It is the simplest olefin because both of its double bond carbon atoms are not substituted but only attached to hydrogen atoms (Al-Megran & Xiao, 2016). The large global demand for ethylene originates from its various application as raw materials to polymers such as polyethylene found in plastics, or as surfactant chemicals such as ethylene glycol or ethylene oxide (Fan et al., 2013). The global ethylene market grew to a value nearly $222.1 billion in 2019 at a compound annual growth rate CAGR of 5.25% since 2015, and is expected to grow at a CAGR of 4.77% to nearly $267.6 billion by 2023 (prnewswire.com).

According to Ametek (2019), over 150 million tons of ethylene is produced yearly from petrochemical and chemical industries globally. Traditionally, ethylene is produced by steam cracking of hydrocarbons, and the method continues to dominate the industry (Fan et al., 2012).

Over the years, the technology to produce ethylene from lignocellulosic has been under development. Lignocellulosic biomass, a renewable bioresource for second-generation biofuel production comprises primarily of lignin, cellulose and hemicellulose. The cellulose and hemicellulose have the potential of been hydrolyzed or enzymatically degraded to glucose and a variety of pentose and hexose sugar (Kim et al., 2012). Oil palm empty fruit brunch (EFB) is an example of lignocellulosic byproduct generated from the palm oil industry. Generally, palm oil industry has to dispose about 1.1 ton of EFB per ton of oil produced (Shinoj et al., 2011; Vijaya et al., 2008). EFB generally contains 42.7 – 65% cellulose, 17.1 – 33.5% hemicellulose, 13.2 – 25.31% lignin and 1.3 – 6.04% ashes (Cui et al., 2014).

EFB produced by most palm oil industry has been usually burned in incinerators causing environmental pollution, thus its usage as a source of biofuel reduces the harm it creates to the environment. Sukiran et al. (2009) investigated the pyrolysis of oil palm EFB to produce bio-oils as well as the effects of the particle size of the bimass and the parameters of fast pyrolysis process on the properties of bio-oils. Chiese and Gnansounou (2014) investigated the use of EFB for bioethanol production, comparing the use of dilute acid and dilute alkali for its pretreatment. EFB contains sugar polymers that must be broken down to fermentable sugars (saccharification) by enzymes before being fermented via ordinary techniques. Unfortunately, the cellulose contained in EFB is located in cell walls that create resistance to possible enzymes attack. These cell walls must be disrupted to enable possible attack by the enzymes, thus the need for a physicochemical pretreatment on the EFB feedstock (Chiesa & Gnansounou, 2014). Aside breaking the resistance on cellulose attack, pretreatment is also necessary to reduce the hemicellulose and lignin content for effective fermentation and increase in pore size. EFBs are one of the cheapest feedstocks found as alternative to renewable bioresource. The bioconversion of EFB fibres to fermentable sugars requires delignification pretreatment followed by hydrolysis of the recovered cellulose and hemicellulose to sugars. Such treatment is essential for effective production of sugars as lignin prevents the hydrolytic enzymes from having effective contact with the cellulose and hemicellulose. Several studies have investigated the effects of some pretreatment processes, such as aqueous ammonia soaking pretreatment (Jung et al., 2011), pretreatment with steam (Shamsudin et al., 2012), alkaline pretreatment (Choi et al., 2013) and sequential pretreatment with dilute acid and then alkali (Kim et al., 2012).

Kim et al. (2012) investigated the usage of sequential acid/alkali to pretreat EFB, and they achieved a treated feed consisting of 82% cellulose, less than 1 % hemicellulose and 30% lignin, which shows that the treatment process is effective. Medina et al., (2016) investigated the use of steam explosion pretreatment on EFB. Their result showed an increase of 24% in cellulose and 68% reduction in hemicellulose, however there is need for subsequent transformation process to obtain precursors for value-added products, enhancing the sustainability of EFB processing plants.

Palamae et al. (2017) utilized a sequential two-step treatment with peracetic acid and alkaline peroxide to remove 98% of the lignin from oil palm empty fruit brunch. All the above research work listed, presented pretreated biomass that morphologically revealed rough, porous and irregular ordered surfaces for enhancing enzyme digestibility.

This proposes work is aimed to technically and economically investigate the feasibility of a bioethylene plant using EFB as the primary feedstock. Aspen Plus simulation tool will be used for the simulation and economic analysis will be conducted on the simulated bioethylene process plant with the aid of ICARUS program available in Aspen Plus version 10.

Materials and Methods

The scope will be limited to the use of the software to demonstrate how an EFB processing plant can be created and tested virtually, based on the data obtained from experiments published in the literature. Aspen Plus was used for the simulation to run and test the proposed pretreatment, reaction and product purification pathway. The composition of the feedstock used for the process simulation is shown in Table 1.

Table 1. Composition of the EFB feed

Component	Weight Fraction
Cellulose	0.3885
Xylan	0.1307
Arabian	0.1307
Solslds	0.1599
Ligin	0.1062
Ash	0.014
Water	0.07

The ethylene production process involves pretreatment, reaction at different stages, and the purification process of the product. Due to the unavailability of kinetic data, all reactors will be modeled as conversion reactions favoring the desired product and suppressing the undesired product.

Feed Pretreatment

EFB contains sugar polymers that must be broken down to fermentable sugars (saccharification) by enzymes before being fermented via ordinary techniques. Unfortunately, the cellulose contained in EFB is located in cell walls that create resistance to possible enzymes attack. These cell walls must be disrupted to enable possible attack by the enzymes, thus the need for a physicochemical pretreatment on the EFB feedstock. Aside breaking the resistance on cellulose attack, pretreatment is also necessary to reduce the hemicellulose and lignin content for effective fermentation and increase in pore size. The bioconversion of EFB fibres to fermentable sugars requires delignification pretreatment followed by hydrolysis of the recovered cellulose and hemicellulose to sugars. Such treatment is essential for effective production of sugars as lignin prevents the hydrolytic enzymes from having effective contact with the cellulose and hemicellulose.

Process Description

A processing capacity of 100,000 kg/day of empty fruit brunch was considered, assuming 60% of EFB waste from the nation’s crude palm oil processing facilities can be collected and converted to useful product.

EFB Feed Pretreatment

The washed EFB feed from storage is fed to the crusher where size reduction of an average particle size of 2mm is achieved. The crushed feed is sent to the steam explosion vessel where intimate contact between the EFB and steam, with the process condition of the steam set at 210^{o}C and 18 bar. This helps to degrade the complex structure of the lignocellulosic biomass. Stream from the steam explosion vessel is further preheated by washing with hot water at 80^{o}C, and fed to the digester for wet oxidation using hydrogen peroxide (H_2O_2) and diluted soda solution (5 g/L NaOH) at 70^{o}C for further degradation of hemicellulose and lignin component in the stream. The digester is modelled as a conversion reactor.

Saccharification and Fermentation Reaction

The stream from the digester is cooled to 65^{o}C and fed to SSF reactor where it is hydrolyzed using commercial cellulase, converting the cellulose content in the stream to glucose. From the digester, the stream is fed to the fermentation reactor after cooling to reaction temperature of 38^{o}C. Yeast is added to the fermentation reactor where it acts on the glucose and gets it converted to ethanol (17wt%).

Ethanol Recovery and Conversion to Ethylene

Purification of the product stream from the fermentation reactor to yield ethanol of 99% purity was done with a distillation column and a mechanical sieve in series. The distillation column was modelled to recover ethanol near the azeotrope point. The vapor product from the molecular sieve is compressed and heated to attain a reaction condition of 43 bar and 360°C, and then fed to the reactor where dehydration reaction takes place, with the removal of water molecule from the ethanol structure and yielding of ethylene. Product from the reactor is compressed and cooled using chiller to achieve a two-phase fluid of ethylene-water mixture. The ethylene is then recovered at the final separator with a product purity of 99.3%.

Results and Discussion

The simulated model as shown in Figure 1 displays the individual unit operations needed for the conversion of EFB to ethylene. Table 2 shows the composition data of the ethylene product achieved, with a molecular weight of 27.97.

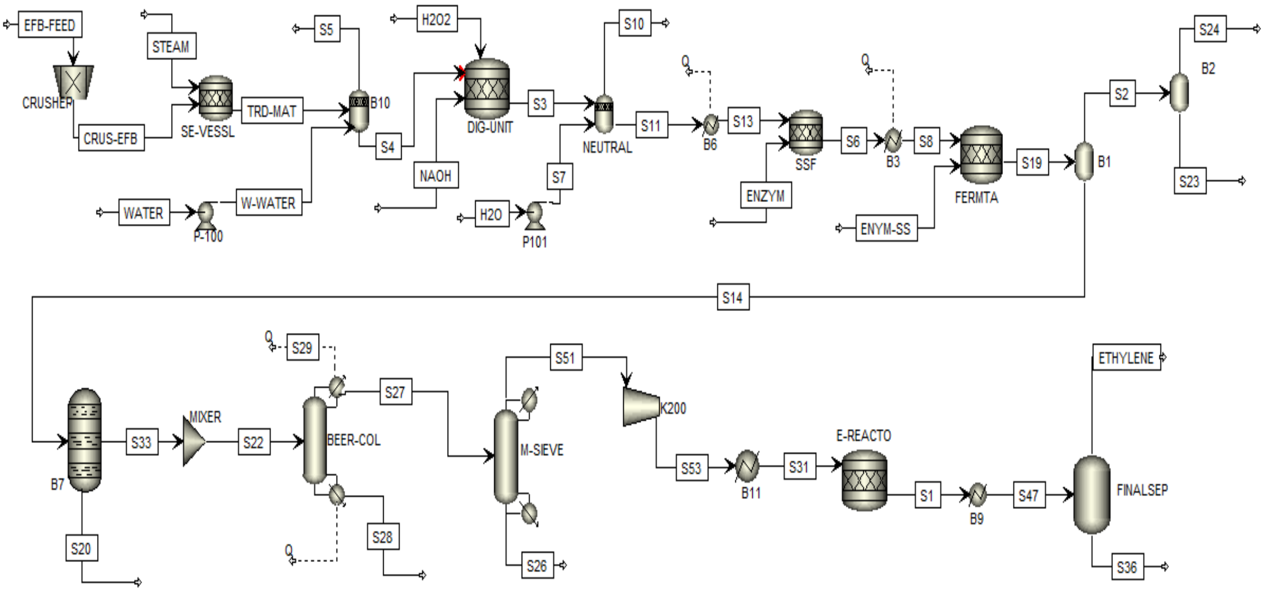

Figure 1. Aspen Plus simulated model for bioethylene production process

Table 2. Mass composition of the ethylene product stream

	Units	ETHYLENE
− Mass Fractions		
WATER		0.000873159
GLUCOSE		6.15422e-31
ETHANOL		0.000162545
ETHYLENE		0.993142
DIETH-01		0.00401897
XYLAN		0
ARABINAN		0
EFB		0
CELLULOS		0
LIGNIN		0
ASH		0
CELLULAS		0

Economic Analysis

Economic analysis was conducted on the simulated bio-ethylene plant with the aid of ICARUS program available in Aspen Plus version 10. The ICARUS program is meant for economic evaluation and investment analysis for any simulated process plant on the Aspen environment. Table 3 summarizes the plant capital cost, with the total project cost of $18.4 million (₦7.54 billion), with the largest amount to be spent on purchasing required equipment. The dollar exchange rate is kept at $1 to ₦410.

Table 3. Summary of Plant Capital Cost

PROJECT CAPITAL SUMMARY	Total Cost (USD)	Naira Equivalent
Purchased Equipment	7,130,000	2,923,300,000
Equipment Setting	85,243.20	34,949,712
Piping	1,550,000	635,500,000
Civil	303,410	124,398,100
Steel	160,206	65,684,460
Instrumentation	1,510,000	619,100,000
Electrical	850,157	348,564,370
Insulation	347,693	142,554,130
Paint	84,661.80	34,711,338
Other	5,520,000	2,263,200,000
Subcontracts	0	0
G and A Overheads	444,713	182,332,330
Contract Fee	665,824	272,987,840
Escalation	0	0
Contingencies	3,360,000	1,377,600,000
Total Project Cost	22,000,000	9,020,000,000
Adjusted Total Project Cost	18,400,000	7,544,000,000

Operating Cost

Operating Cost of Project Operating cost which comprises labor cost, utility cost, operating charges, plant overhead, general and administrative (G & A) cost is shown in Table 4. The raw materials used for this project with their respective cost based on Nigerian market prizes are shown in Table 5.

Table 4. Summary of Operating Cost

OPERATING COST	Total Cost	Naira Equivalent
Operating Labor Cost	1,010,000	414,100,000
Maintenance Cost	360,502	147,805,820
Operating Charges	252,023	103,329,430
Plant Overhead	684,296	280,561,360
Subtotal Operating Cost	99,200,000	40,672,000,000
G and A Cost	7,930,000	3,251,300,000
Total	109,436,821	44,869,096,610

Table 5. Summary of Raw material cost

Description	Rate per Hour (Lb/h)	Cost per Hour	Cost Per Annum (USD)	Cost Per Annum (Naira)
ENZYM	2,204.58	1,489.72	13,058,896.13	5,354,147,412
NAOH	22,045.85	34.98	306,694.0697	125,744,568.6
ENYM-SS (Yeast)	522.48	236.95	2,077,142.174	851,628,291.3
EFB-FEED	220,458.55	5,998.89	52,586,337.72	21,560,398,465
H_2O_2	22,045.85	179.96	1,577,532.27	646,788,230.8
TOTAL			69606602.36	28538706968

Revenue from Product Sales

The total revenue derived from bio-ethylene sales is shown in Table 6, based on the assumption that bio-ethylene will cost a little below the price of petroleum-derived ethylene. According to Statistica (2021), as of July 2021, the average price of petroleum-derived ethylene was at 1,014 US dollars per ton ($0.507/lb.). For this design, the selling price of ethylene is placed at $0.454/lb.

Table 6. Revenue from product sales

Description	Rate per Hour (Lb/h)	Cost per Hour	Cost Per Annum (USD)	Cost Per Annum (Naira)
ETHYLENE	35571.13	16132.04	141,413,491.20	57,979,531,377

Profitability Analysis

Table 7 shows the profitability analysis for the first six consecutive years. The cash flow in the first year with a negative value shows that loss will be encountered for the first production year. Profits will be obtained from the second year as observed from the cash flow.

Table 7. Revenue Analysis for the first six years as extracted from generated results

	USD/Yr1	USD/Yr2	USD/Yr3	USD/Yr4	USD/Yr5	USD/Yr6
Revenue	-60000000	41500000	45500000	49700000	54200000	59000000
DEP	1470000	1470000	1470000	1470000	1470000	1470000
E	-61400000	40000000	44000000	48200000	52700000	57500000
TAX	0	16000000	17600000	19300000	21100000	23000000
NE	-61400000	24000000	26400000	28900000	31600000	34500000
TED	-60000000	25500000	27900000	30400000	33100000	36000000
TEX	71400000	114000000	118000000	122000000	126000000	131000000
CF	-60000000	25500000	27900000	30400000	33100000	36000000

Where:
DEP = Depreciation
EBT = Earnings before Tax
NE = Net Earnings (Profit after Tax)
TED = Total Earnings
TEX = Total Expenses, Excluding Tax and Depreciation
CF = Cash Flow for Project
Yr = Year.

Table 8 shows the profitability analysis for the project, with a profitability index of 1.11 indicating that the business is a profitable one. The business will break even in approximately 4 years and two months.

Table 8. Summary of project profitability analysis

PARAMETER	
NPV (Net Present Value)	Negative for the first 4 years and Positive for the rest life span
IRR (Internal Rate of Return)	49.04%
MIRR (Modified Internal Rate of Return)	21.27%
NRR (Net Return Rate)	11.23%
PO (Payout Period)	4.11years
ARR (Accounting Rate of Return)	230.39%
PI (Profitability Index)	1.11

Sensitivity Analysis

Sensitivity analysis was conducted by varying the plant production capacity, unit EFB feed cost and unit ethylene product cost. Aim was to investigate its effect on the net present value of the project. As observed from Figure 1, an increase in production capacity gives a slight increase in the payback period, but gives a reasonable cash flow for the subsequent years throughout the life period of the process plant. Also decrease in production capacity will increase the negative values of NPV, thus at a point (e.g., 25000kg/hr) the proposed plant at a lesser capacity will not be profitable. Figure 2 and 3 indicates effect on the NPV values by slight variation in the ethylene product price and the EFB feed price respectively. It can be observed that the prices of both EFB feed and Ethylene market price plays an important role in the profitability of the proposed plant.

Figure 2. Sensitivity on the NPV by variation in ±50% plant design capacity

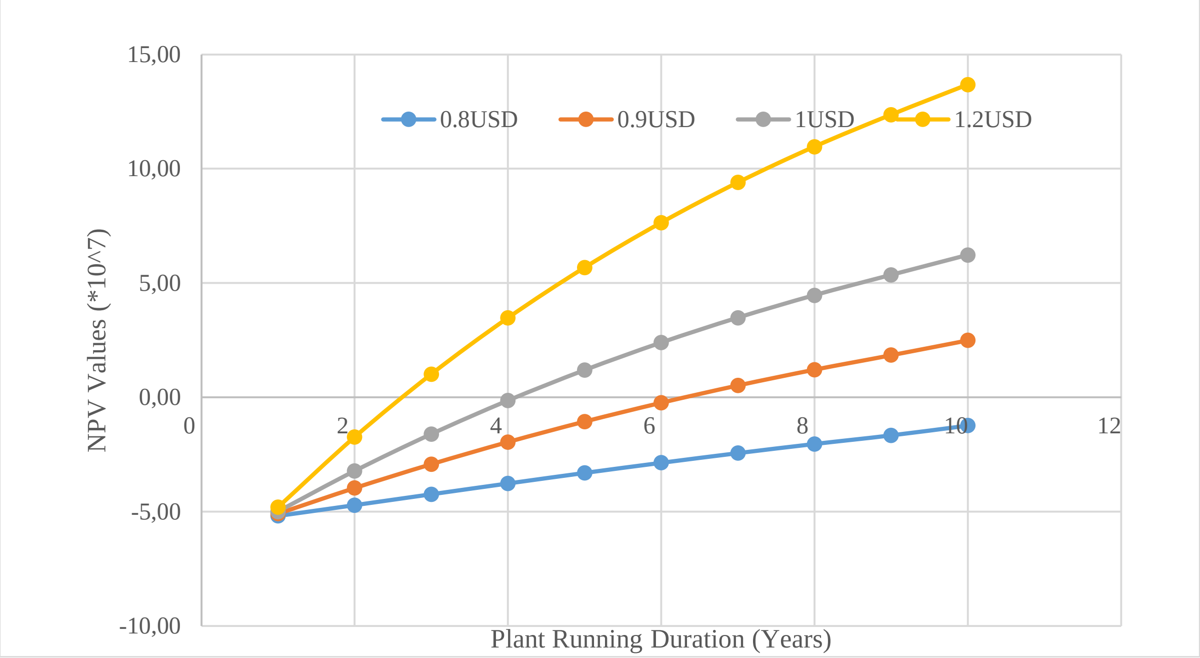

Figure 3. Sensitivity of NPV by varying the price of ethylene product

Figure 4. Sensitivity of NPV by varying the price of EFB Feed

Conclusion

The techno-economic analysis confirms that the simulated plant treating empty fruit brunch to produce 387.24mtpd (16,135 kg/hr) of ethylene is feasible and profitable. EFB is confirmed to be a promising feedstock for biofuel production, unlike the first-generation biomass doesn't affect the human food chain. It is currently seen as a waste product and it can be sourced in large quantities from oil palm industries.

The simulated process technology involves pretreatment of the empty fruit brunch to remove lignin, reduce the crystallinity of the cellulose and increase the porosity of lignocellulosic materials to make the cellulose and hemicellulose more amenable to the following processes; hydrolysis to convert the cellulose and hemicellulose into glucose; fermentation to convert the glucose into cellular energy, producing ethanol and carbon dioxide as by-product; Distillation and molecular sieve adsorption was used to separate azeotropic ethanol-water mixture; dehydration of ethanol to produce ethylene; and recovery of ethylene of above 99% purity.

The economic analysis shows the project is highly profitable and efficient with a payback period of 4.11 years and IRR of 49%. Sensitivity of the NPV was observed by varying the plant production capacity, the cost of EFB feed and the cost of the finished product, and the result indicated a better cash flow for higher plant capacity and higher product price. It is recommended to test the process at a pilot plant level to better simulate real plant conditions.

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