

Communication

Techno-Economic Analysis of an Integrated Bio-Refinery for the Production of Biofuels and Value-Added Chemicals from Oil Palm Empty Fruit Bunches

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Abstract: Lignocellulose-rich empty fruit bunches (EFBs) have high potential as feedstock for second-generation biofuel and biochemical production without compromising food security. Nevertheless, the major challenge of valorizing lignocellulose-rich EFB is its high pretreatment cost. In this study, the preliminary techno-economic feasibility of expanding an existing pellet production plant into an integrated bio-refinery plant to produce xylitol and bioethanol was investigated as a strategy to diversify the high production cost and leverage the high selling price of biofuel and biochemical. The EFB feedstock was split into a pellet production stream and a xylitol and bioethanol production stream. Different economic performance metrics were used to compare the profitability at different splitting ratios of xylitol and bioethanol to pellet production. The analysis showed that an EFB splitting ratio below 40% for pellet production was economically feasible. A sensitivity analysis showed that xylitol price had the most significant impact on the economic performance metrics. Another case study on the coproduction of pellet and xylitol versus that of pellet and bioethanol concluded that cellulosic bioethanol production is yet to be market-ready, requiring a minimum selling price above the current market price to be feasible at 16% of the minimum acceptable return rate.

Keywords: empty fruit bunches; pellet; xylitol; bioethanol; integrated process

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1. Introduction

Malaysia is currently the world's second-largest palm oil producer after Indonesia. As in 2019, 5.90 Mha of land in Malaysia is covered with oil palms, 46.9% of which is in peninsular Malaysia, and the remaining 26.1% and 26.9% are in Sabah and Sarawak, respectively [1]. With the rapid expansion of the palm oil industry in Malaysia, sustainability issues related to oil palm have accelerated in recent years [2], especially environmental issues associated with the palm oil industry. These issues have increased the urgency for the industry to find a balance between environmental and economic sustainability. One of the many options is to convert the excessive biomass leftover from the palm oil mills, especially the empty fruit bunches (EFBs), into value-added biomass and generate revenue from the waste [3]. EFBs are the remaining parts after oil palm fruitlets are stripped from fresh fruit bunches (FFBs) [4,5]. According to Hamzah et al. [6], the amount of EFB produced is estimated to be 22% of the FFB (in wet weight), which is the largest proportion of oil palm plantation solid waste. Based on the FFB yield data from MPOB (2019) [7], it is estimated that the average total amount of EFB produced from 2017 to 2019 is 22.42 million tons annually. EFB is considered a waste that needs to be continuously removed to avoid piling at the site because it can lead to methane emissions that contribute to air pollution and

negative health impacts [8,9]. Conventionally, EFB is used as a mulch or organic fertilizer in oil palm plantations because of its high alkali content or fuel in the boiler to reduce diesel consumption [10,11]. However, feeding EFB directly into the boiler without removing its alkali content contributes to slagging and fouling, which will eventually reduce the operation efficiency of the boiler [12]. In addition, EFB is a lignocellulosic material that can potentially be utilized to produce high-value-added products such as biofuel, biochemical materials, industrial sugar, and biofertilizer. If the potential is unlocked and fully exploited, the palm oil industry will be one step closer to sustainable development and circular economy [13].

There were several studies related to the valorization of EFB to fuel (pellets, briquettes, bioethanol) and value-added products (charcoal, long fibers, biochemical) as a promising and sustainable alternative to the replacement of fossil fuels and chemical products [14–49]. The lignocellulose composition of EFB consists of 36–43% cellulose, 15–25% hemicellulose, and 22–34% lignin [20], as well as approximately 4% ash or mineral content [21] that contains compounds such as K_2O , P_2O_5 and SiO_2 , which can be a suitable source for pellet, biofertilizer, xylitol and bioethanol production. Instead of burning EFB as a fuel directly, processing EFB into pellets by increasing its lignin content and removing its mineral content improves the calorific value [22,23]. Renewable solid fuel for power generation is in high demand in Europe, Japan, Korea, and China. Currently, an industrial establishment in Malaysia has the capacity to produce 1000 to 3000 tons of pellets monthly [24], but the average annual global growth of pellet demand is of 960,000 tons/year [25–27]. This huge supply–demand mismatch offers an opportunity for EFB pellets to fill in the supply gap because of their cost competitiveness, low moisture content, high calorific value, and low smoke and fume generation during combustion [28]. Cellulosic bioethanol is considered a second-generation (2G) biofuel produced from the cellulose component of EFB. 2G biofuel has gained considerable demand because it offers an alternative to minimize possible conflicts between fuel and food security [29]. However, cellulosic bioethanol is inherently more challenging to produce than sugar- or starch-based bioethanol and more costly than fossil-based ethanol. Hence, it is necessary to produce valuable biochemicals such as xylitol simultaneously with 2G cellulosic bioethanol to improve the overall feasibility of the production process [30]. EFB with a substantially high amount of polymeric xylan (hemicellulose) is a suitable xylose source for xylitol production. Xylitol is a highly sought value-added product in the food and pharmaceutical industries. It can only be extracted from plant biomass [31]. The global demand for xylitol is approximately 125,000 tons, with an average market price of 5000 to 20,000 USD/ton, and xylitol is mostly used as a substitute for sugar because of its lower caloric content but with a similar sweetening power [32].

Although the demand for these products is high worldwide, the recalcitrant structure of lignocellulose in EFB is the bottleneck to yield high amounts of bioproducts [33,34]. Therefore, multiple pretreatment steps are required to fractionate the complex structure, increase the EFB porosity, reduce cellulose's crystallinity, solubilize hemicellulose, and modify the lignin structure [35–37]. These pretreatment methods include physical, biological, and chemical processes to condition the EFB before feeding to the pellet and biochemical production. The physical method aims to reduce the particle size and crystallinity of biomass by milling, grinding, or chipping. Further processing of biomass is easier and more effective. Biological methods use microorganisms such as fungi and bacteria to degrade lignin, hemicellulose, and cellulose. Biological methods are usually cost-effective, have low energy requirements, and are environmentally friendly. No chemical waste is generated, but the degradation process is slow. Either acid or alkali is often used to treat biomass in chemical treatment [38]. A combination of physical and chemical methods has also been used to reduce the recalcitrance of lignocellulosic biomass. The most commonly used physicochemical methods are liquid hot water, steam explosion, microwave pretreatment, and ozonolysis treatment [39–42]. Most of these physicochemical methods are conducted at a high temperature and pressure to accelerate biomass degradation. Still, these methods are less efficient because they can cause severe degradation of the EFB components [43].

There were three main processes in producing EFB pellets: moisture removal, composition adjustment (lignin increment and ash reduction), and pellet densification. Removal of high alkali content in EFB, such as K and Na, in the form of ash, is a crucial step to produce premium-grade pellets for boiler applications. The ash deposition of EFB can be removed with washing treatment. This washing process's effluent contains essential nutrients for plant growth and can be a suitable source of N-P-K fertilizers [44]. In addition, EFB contains highly hydrophilic hemicellulose and has approximately 67% moisture. It requires a high intensity of drying and hemicellulose removal to be used as fuel in the boilers. The removal of hemicellulose content increases the lignin percentage, which has a high calorific or heating value [23,45]. Pretreatment processes such as torrefaction, steam explosion, and hydrothermal treatment are commercial thermal treatment techniques to improve the calorific value [46]. Torrefaction is a heat treatment process to carbonize EFB and increase its C/O ratios [47]. Torrefaction also reduces the moisture content of EFB. It reduces the mass by almost half, enhancing the transportability and prolonging the storage duration of pellets [48]. Steam explosion uses high-temperature saturated steam to penetrate through the cell wall structure at high pressure and solubilize hemicellulose [41]. Upon instantaneous controlled pressure drop, the cell wall expands adiabatically and undergoes explosive decompression, making cellulose more accessible [23]. Hydrothermal treatment (HTT), also known as wet torrefaction, is another pretreatment process suitable for biomass with high moisture content, with a typical treatment temperature of 150 to 350 °C [49]. Both Ahda et al. [50] and Novianti et al. [45] have shown that the HTT process upgrades the EFB into more stable, hydrophobic, and more lignin-containing feedstock with lower mineral content. While pretreatment of EFB in pellet production improves the fiber's quality, the loose EFB fiber is usually bulky and low in density. The densification process can increase the energy potential of the biomass. There are two densification methods: screw press and piston press. Pellets produced through this process can be used in direct combustion for energy generation [28].

In a coproduction of bioethanol and xylitol, EFB is first chemically pretreated with dilute acid or alkali to extract cellulose from EFB [51] to produce hydrolyzed hemicellulose or xylose [20]. Acid hydrolysis pretreatment is commonly used because it can hydrolyze hemicellulose, which has a lower degree of polymerization and amorphous structure, much faster than cellulose. The pretreatment process was able to increase the cellulose content from 41% to 72% [52–55]. The most commonly used acid is diluted sulfuric acid at a concentration below 4% (*w/w*) [56]. Other mineral acids, such as hydrochloric, nitric, and phosphoric acids, can be used, but sulfuric acid results in an efficient process, lower cost, and shorter reaction time [57].

For bioethanol production, the cellulose-rich hydrolysate undergoes subsequent hydrolysis in either biological method through enzymatic hydrolysis or chemical method through acid hydrolysis. The enzymatic hydrolysis method is preferable because it is cost-effective and produces a higher sugar content than acid hydrolysis [58,59]. Enzymatic hydrolysis degrades cellulose into simple sugar by cellulolytic enzymes, which require an optimal temperature between 45 and 55 °C and a pH range of 4–5 [36]. Ghazali and Makhtar [60] used cellulase enzymes produced from the fungus *Trichoderma reesei* to increase glucose yield. The enzymes produced a constant maximum yield of 2.5 g/L at an enzyme to substrate ratio of 0.05 (0.5 g enzyme/10 g EFB) at 50 °C and pH 5. Zhai et al. [51] reported that the sugar yield was improved from 30.5% to 66.9% by increasing the enzyme dose from 10 to 60 FPU/g EFB at 50 °C and pH 4.8. Both studies have indicated that optimal enzymatic hydrolysis conditions, such as temperature, pH, and substrate concentration, are essential in improving sugar yield [61]. Other fungi can be used to produce enzymes, but *Trichoderma reesei* is the most commonly used fungus in industrial enzymatic processes [62]. The sugar from enzymatic hydrolysis is fermented with yeast to produce bioethanol. The most frequently used yeast is *Saccharomyces cerevisiae* because it can provide a high ethanol yield [59,63]. Sugar can be fermented into ethanol by two processes: separate hydrolysis and fermentation (SHF) and simultaneous saccharification and fermentation (SSF). For

an SHF system, both operating conditions of hydrolysis and fermentation are operated independently at different optimal conditions. Using this method, the optimization and control of the process conditions, such as the temperature and pH of the hydrolysis and fermentation, can be performed effectively [64]. In contrast, SSF system performs better than SHF, where SSF has a shorter processing time, lower cost, and higher bioethanol yield. Nevertheless, it is challenging to obtain optimum pH and temperature conditions for both saccharification and fermentation in the SSF system. Dahnum et al. [64] showed that SSF has a shorter processing time of 72 h than SHF in producing bioethanol at a temperature of 32 °C and pH of 4.8. Similarly, Sukhang et al. [55] concluded that SSF provided a higher bioethanol yield of 0.281 g/g EFB than SHF, with a yield of 0.258 g/g EFB at a temperature of 36.94 °C and pH of 4.5. Both studies implied that the optimal temperature for both enzyme and yeast activity was in the range of 32 °C to 39.8 °C, while the pH was acidic in the range of 4.0–5.0 [59].

For xylitol production, the hydrolyzed hemicellulose (xylose) from the pretreatment is further converted to xylitol via chemical (hydrogenation) or biological (fermentation) routes [65]. In the chemical route, xylitol production consists of three stages after the pretreatment stage: xylose purification, catalytic hydrogenation, and xylitol purification. Xylose purification is essential to obtain a high concentration of xylose, reduce unwanted side products and deactivate the acid catalyst used [31,57]. The hydrogenation step occurs in the presence of the Raney-nickel catalyst. This catalyst is widely used in industry because it offers a high yield of 80% to 95% xylitol and conversion efficiency of 98% [66–68]. Then, the produced xylitol is purified with filtration or ion exchange to recover xylitol at higher purity. At the industrial level, the chemical route is commonly used [31,68], but the drawbacks are high separation and purification costs, high energy consumption, and environmental impacts, such as toxic catalysts and high-pressure hydrogen gas [65]. The biological route has recently become more attractive because the process is sustainable and has a lower cost than the chemical route. Yeast that belongs to the genus *Candida* sp. [69] can convert xylose into xylitol with a yield of up to 90% [66]. Another report from Tamburini et al. [70] showed that the genus *Candida* sp. can produce xylitol at a maximum yield of 86.84% at 32 °C, 80 g/L xylose and pH 2.5. Nevertheless, the biological route's limitations are the expensive separation process of xylitol from the fermentation broth and the toxicity effects of xylitol to yeast [31,57]. Kresnowati et al. [71] proposed using ultrafiltration membrane technology to obtain high xylitol concentrations from fermentation broths. The proposed method has the potential for energy savings and higher purity, but the fouling problems need to be addressed.

According to the Malaysia National Biomass Strategy 2020 [72], pellet production is identified as a low entry point to generate wealth from biomass because of its technological maturity, relatively low capital investment, and short payback time. Expansion investment to produce 2G biofuels and biochemicals has a higher risk; however, the potential value creation is up to 5 times the revenue of pellets per dry ton of solid biomass input. In the long term, valorizing EFB biomass will minimize waste and recover more valuable products that will increase the profitability of the investment. More effort is required to remove the barriers of unfavorable high processing costs and low profitability of final products [20,73]. Therefore, a techno-economic feasibility study of an integrated bio-refinery to produce pellets, xylitol, and bioethanol was developed and evaluated in this work. The aim is to identify the process that is profitable with the production of these three products. If the higher-value biochemicals global market materializes earlier, EFB can be swiftly diverted to these biochemicals' production. In this work, a pilot scale pretreatment plant in Malaysia was used as a case study to investigate the potential to expand the products to pellets, biofertilizer, xylitol, and bioethanol. The respective products' market demand, technological production, and economic potential are investigated as well.

2. Methodology

The following section describes the methodology required to develop the analysis. Figure 1 shows the flow of techno-economic analysis of the bio-refinery plant starting from developing the process flow diagram until evaluating the economic performance metrics of different scenarios. The first step was to develop the process flow diagram (PFD) of a bio-refinery to produce pellet, xylitol and bioethanol from empty fruit bunches, where feed-in streams, output streams, conversion factor, process flow, unit operations and its corresponding operating conditions were identified. The law of mass conservation is still applicable even though there are chemical reactions and physical transformations of feedstock. Thereafter, materials balance was performed by accounting for the materials entering and leaving the system. With the mass balance information, the total capital investment (TCI), total production cost (TPC) and revenue were estimated. The net present value (NPV), return on investment (ROI), payback period (PBP) and internal rate of return (IRR) were calculated from the cash flow analysis based on the predefined scenarios. It should be noted that both TCI and TPC were only preliminary estimations due to the limited data available. However, the estimations will not affect the overall analysis at different scenarios because the comparisons were made on the same ground.

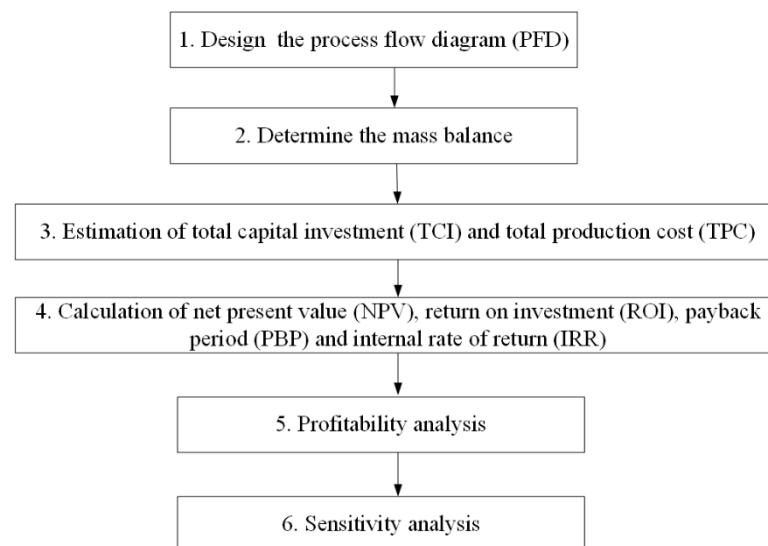


Figure 1. Methodology of techno-economic analysis.

2.1. Process Design Description

The bio-refinery was designed based on an EFB feedstock capacity of 126,720 tons/year with an actual annual operation of 5280 h (330 days, based on the existing pellet production plant) to produce three main products: pellet, xylitol, and bioethanol. The process flow diagram of the bio-refinery is shown in Figure 2. The detail process description is described in Sections 2.1.1 and 2.1.2 below. The EFB feedstock was split into two streams, one for pellet production and the other for xylitol and bioethanol. In this study, the profitability of the coproduction of these three products was investigated based on the splitting ratio between these two streams. Table 1 shows an example of the material balance of the bio-refinery at 30% EFB fed into the pellet production plant.

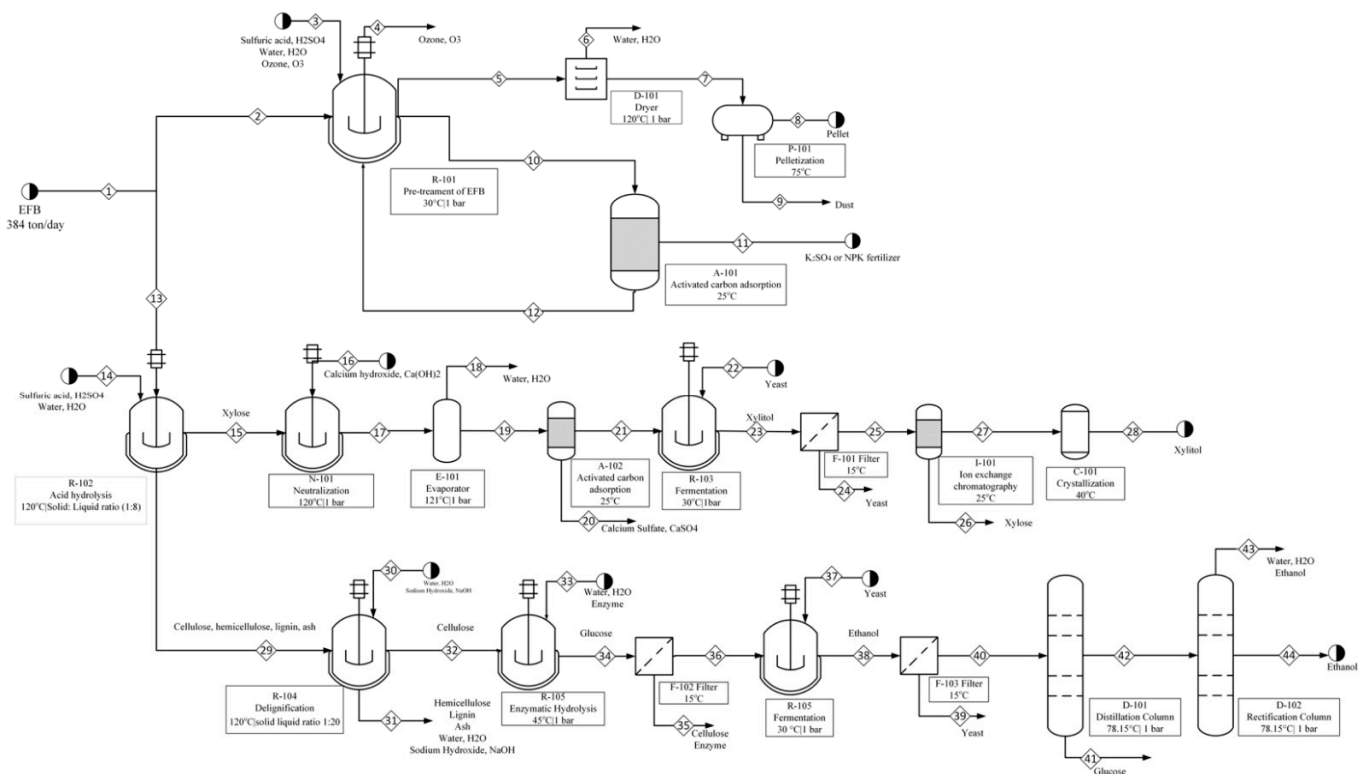


Figure 2. Process flow diagram of the proposed integrated bio-refinery.

Table 1. Overall Mass Balance Summaries at a 30% EFB Splitting Ratio to Pellet Production.

Materials		Consumption or Yield (ton/day)
In	EFB (dry)	384.00
	Water (H ₂ O)	5776.40
	Sulfuric acid (H ₂ SO ₄)	27.46
	Ozone (O ₃)	8×10^{-3}
	Calcium hydroxide (Ca(OH) ₂)	20.31
	Sodium hydroxide (NaOH)	31.21
	Enzyme	0.88
	Yeast	12.54
Total		6252.79
Out	Delignification residue	122.17
	Water (H ₂ O)	5786.27
	Sulfuric acid (H ₂ SO ₄)	0.58
	Depleted ozone (O ₃)	8×10^{-3}
	Calcium sulfate (CaSO ₄)	37.31
	Sodium hydroxide (NaOH)	31.21
	Spent enzyme	0.88
	Spent yeast	12.54
	Xylose	0.96
	Glucose	29.17
	Xylitol	72.75
	Bioethanol	43.75
	Pellet	100.80
	Dust	10.86
	Fertilizer	3.54
Total		6252.79

2.1.1. Pellet Production Plant

The EFB feed for pellet production is pretreated with solvents consists of dilute sulfuric acid (H_2SO_4) (0.5% *w/w*), ozone (O_3) ($6.92 \times 10^{-4}\%$ *w/w*) and water (H_2O) (10 ton/ton of EFB) in the pretreatment reactor (R-101) at 180 °C and 1 bar [74]. The pretreatment process is aiming to exposing its cellulose, hemicellulose and lignin fraction and reducing the amount of ash content in the EFB [45]. Table 2 shows the EFB compositions before and after the pretreatment. The pretreated EFB is then dried (D-101) at temperature of 120 °C and pressure of 1 bar, which has a moisture content of approximately 50 wt% [75,76]. The dried EFB is then fed into the pelletization chamber (P-101) to produce pellet at 75 °C and at a maximum compression pressure of 200 MPa [77]. About 87.5% of raw EFB is converted into pellet form and the remaining is dust [78]. Meanwhile, the effluent from the pretreatment reactor (R-101) contains of 3.08% dissolved solids [74] is fed into the activated carbon adsorption (A-101) at 25 °C to separate solubilized N, P and K nutrient [79]. The solvent is recycled back to be used in the pretreatment stage while the remaining solid is removed as fertilizer.

Table 2. Overall Mass Balance Summaries at a 30% EFB Splitting Ratio to Pellet Production [74,80].

Chemical Composition	Percentage (wt%, Dry Basis)	
	Raw EFB	Pretreated EFB
Cellulose	45.2%	80.8%
Hemicellulose	29.5%	6.0%
Lignin	23.6%	13.0%
Ash	1.7%	0.3%

2.1.2. Xylitol and Bioethanol Production Plant

The EFB feed for xylitol and bioethanol production is pretreated with dilute acid in the acid hydrolysis reactor (R-102) with H_2SO_4 (1.25% *w/v*) and water at 120 °C and at a solid-liquid ratio of 1:8 [75,81]. At these reaction conditions, 93% of hemicellulose is converted into soluble xylose, whereas the remaining insoluble hemicellulose, cellulose and lignin are separated as feedstock for bioethanol production. The xylose fraction thereafter is dosed with calcium hydroxide ($\text{Ca}(\text{OH})_2$) in neutralization reactor (N-101) to neutralize the H_2SO_4 at 130 °C [75,82]. The amount of $\text{Ca}(\text{OH})_2$ consumed is 0.77 ton/ton of H_2SO_4 used in the acid hydrolysis process [75,83]. The neutralized xylose is sent to the evaporator (E-101) to remove the moisture content at 121 °C and then to the activated carbon adsorption unit (A-102) at 25 °C to remove calcium sulfate (CaSO_4) (1.25 ton/ton of $\text{Ca}(\text{OH})_2$) formed during the neutralization process [75,79]. Xylose is then fermented with *Candida guilliermondii* yeast (0.17 ton/ton xylose) in fermentation reactor (R-103) to produce xylitol at 30 °C with a yield of 98.7% [75]. The fermented liquid containing xylitol is filtered (F-101) to remove the yeast. The xylitol is then purified using ion-exchange chromatography (I-101) at 25 °C and crystallized with a crystallizer (C-101) and 40 °C to obtain xylitol in the form of solid crystal [75].

The cellulose and lignin-rich solid phase that leaves the acid hydrolysis reactor (R-102) is further processed for bioethanol production. The solid is first treated with 2% (*w/v*) sodium hydroxide (NaOH) solution in the delignification reactor (R-104) at a solid-liquid ratio of 1:20 and at 120 °C [75]. The treatment aims to remove lignin and other components from cellulose. Delignification process is an important step to liberate cellulose and hemicellulose from their complex with lignin, so that these compounds can undergo hydrolysis to produce fermentable sugars. The effluent that is in the form of black liquor, containing hemicellulose, ash, NaOH and water, is removed from the delignification reactor as waste. The cellulose-containing stream is fed into enzymatic hydrolysis reactor (R-105) to further degrade into glucose at temperature of 45 °C [75]. *Trichoderma reesei* cellulase with a consumption rate of 0.02 ton/ton of ethanol is used as the enzyme [74]. The hydrolysis process produces 60% of glucose-rich hydrolysate [75]. The glucose is then separated from

the solid residue containing unreacted cellulose and enzyme in the filter unit (F-101). The glucose is fermented to produce ethanol in fermentation reactor (R-105) at 30 °C, using *Zymomonas mobilis* yeast with a consumption rate of 0.0004 ton/ton of ethanol [84]. This process converts 60% of glucose into bioethanol [75]. The bioethanol-containing stream is separated from the solid residue containing the yeast in the filter unit (F-102) and the unreacted glucose or stillage using distillation column (D-101) at 78.15 °C [85]. The bioethanol is finally dehydrated with rectification column to remove excess water (D-102) at 78.15 °C [74].

2.2. Estimation of Total Capital Investment (TCI) and Total Production Cost (TPC)

The total capital investment (TCI) of the bio-refinery was estimated using the power law or exponential method and Chemical Engineering Plant Cost Index (CEPCI), as shown in Equations (1) and (2), respectively.

$$C_2 = C_1 \times \left(\frac{S_2}{S_1} \right)^n \quad (1)$$

where

C_1 = Cost of the reference plant at capacity of S_1 ;

C_2 = Cost of the plant at desired capacity of S_2 ;

n = Scale exponent or cost-capacity factor.

The cost of the plant at the desired capacity (C_2) is the result of multiplication between the reference plant cost (C_1) and the capacity ratio of the new capacity (S_2) to the reported capacity (S_1), to the power of sizing exponent (n). The n value of 0.6 was used in this preliminary study because a typical chemical plant typically follows the six-tenths rule [86].

$$TCI_{p,x,b} = \sum_{p,x,b} C_2 \times \frac{CEPCI_{new}}{CEPCI_{install}} \quad (2)$$

where

$TCI_{p,x,b}$ = Total capital cost of the bio-refinery;

C_2 = Cost of the plant at desired capacity;

$CEPCI_{new}$ = Chemical engineering cost price index at present year;

$CEPCI_{install}$ = Chemical engineering cost price index at reference year.

As shown in Equation (2), the cost of the desired plant capacity (C_2) is then scaled to the desired time value of TCI using the CEPCI, which is a dimensionless number to estimate the capital cost from the past year to the year 2020. The total capital investment of all three products, $TCI_{p,x,b}$, is the summation of all three TCI estimated individually from their respective CEPCI at its respective year. The reference capital, capacity and $CEPCI_{install}$ of pellet, xylitol, and bioethanol production plant used for this study are listed in Table 3. All CEPCI values were obtained from chemengonline [87], where the $CEPCI_{new}$ of year 2020 is 588.06.

Table 3. Total capital investment of individual pellet, xylitol, and bioethanol production plant.

Products	Cost of the Reference Plant, C_1 (Million USD)	Production Capacity, S_1 (Ton/Year)	$CEPCI_{install}$ Value	Ref.
Pellet	14.05	110,880	CEPCI (2018): 603.10	[74]
Xylitol	220.06	30,624	CEPCI (2016): 541.70	[88]
Bioethanol	40.58	9966	CEPCI (2016): 556.80	[82]

It should be noted that the TCI is estimated based on order of magnitude with limited information, hence the accuracy range is rather wide. Nonetheless, such simplified method allows us to estimate the cost quickly at a different EFB splitting ratio to pellet production.

The total production cost (TPC) is the total cost incurred for the production of a particular amount of products. The TPC consists of two components, namely cost of manufacturing, $COM_{p,x,b}$ and general expenses, $GE_{p,x,b}$, as shown in Equation (3). The COM consists of the variable cost of production, $VCOP_{p,x,b}$, fixed cost of production, $FCOP_{p,x,b}$, and plant overhead, $PO_{p,x,b}$, as shown in Equation (4). Sinnott and Towler [89] have suggested the percentage shares of each component in Equations (3) and (4); these percentage shares are listed in Table 4. The cost of raw materials is listed in Table 5.

$$TPC_{p,x,b} = COM_{p,x,b} + GE_{p,x,b} \quad (3)$$

$$COM_{p,x,b} = VCOP_{p,x,b} + FCOP_{p,x,b} + PO_{p,x,b} \quad (4)$$

Table 4. Summary of percentage shares of TPC [89,90].

Total Production Cost (TPC)	Percentages Share
1. Variable cost (VCOP)	66% of TPC
(a) Operating labor	10% of VCOP
(b) Utility	10% of VCOP
(c) Patents and royalties	6% of VCOP
(d) Direct supervisory and clerical labor	4% of VCOP
(e) Maintenance and repair	4% of VCOP
(f) Operating supplies	4% of VCOP
(g) Laboratory charges	4% of VCOP
2. Fixed cost (FCOP)	10% of TPC
(a) Local taxes	2% of FCOP
(b) Insurance	2% of FCOP
(c) Financial cost (interest)	3% of FCOP
(d) Rent	3% of FCOP
3. Plant overhead cost	9% of TPC
4. General expenses (GE)	15% of TPC
(a) Administrative expenses	5% of GE
(b) Distribution and marketing expenses	10% of GE
(c) Research and development expenses	5% of GE

Table 5. Cost of raw materials.

Raw Material	Cost (USD/Ton)	Ref.
EFB	6	[14]
Sulfuric acid	41	[74]
Enzyme	6310	[84]
Yeast	5700	[84]
Calcium hydroxide	75	[88]
Sodium hydroxide	98	[75]
Water	0.63	[91]

2.3. Calculation of Economic Performance Metrics

There are a few tools that can be used to evaluate the economic feasibility of an investment; some take the time value of money (TVM) into consideration, and others do not. Example tools for the former are NPV and IRR, whereas the latter are PBP and ROI. The tools that do not take TVM into consideration are relatively less complicated and straightforward to use, thus providing a rapid assessment of the viability of a project. However, if the duration length of investment is long, then the tools with TVM provide a more realistic analysis. Eventually, all these tools analyze the cash flow with or without discounted factors from various perspectives to provide a decision-making value for

investors to consider. To begin with, this study considered the project has a life expectancy of 20 years, a 100% TCI was spent in year 0, and the minimum acceptable rate of return (MARR) was set at 16%, which indicates the level of risk of the investment. The level of risk is low because the pellet, xylitol, and bioethanol are considered biorefineries with new capacity with the established corporate market position [92]. The prevailing corporate tax rate was set at 24% in reference to the Inland Revenue Board of Malaysia. Although asset depreciation has no direct impact on cash flow, it changes the tax liabilities. Herewith, the straight-line annual depreciation method was used to estimate the asset depreciation.

NPV, as shown in Equation (5), is the measure of profitability based on the total present value of a time series of cash flows, CF_n , at any time period (n) in years from the present time with an interest rate of i . The interest rate was assumed to be the same as MARR [92]. This method converts the cash flow in the future to present values for comparison. A positive NPV indicates a viable investment. A greater and positive NPV indicates the project is competitive.

$$NPV = \sum_{n=0} \frac{CF_n}{(1+i)^n} \quad (5)$$

The IRR calculation is complementary to the NPV calculation, where it measures the discounted annual rate of return and provides a safety investment margin. The IRR is the interest rate at which NPV is equal to zero, as shown in Equation (6).

$$NPV = \sum_{n=0} \frac{CF_n}{(1+IRR)^n} = 0, \quad (6)$$

The PBP is a profitability measure in terms of the length of time to recover the cost of investment. The limitation of the PBP method is that the cash flows beyond the breakeven year are no longer relevant; thus, it is not able to capture the long-term profitability of the investment. The PBP calculation used for this study was based on uneven cash flows, as shown in Equation (7). The PBP was calculated by adding the final year, n , that has a negative cumulative cash flow with the fraction of the absolute value of cumulative cash flow, CCF_n at n year to the cash flow, CF_n , at $n + 1$ year.

$$PBP = n + \frac{CCF_n}{CF_{n+1}} \quad (7)$$

ROI is a simple measure of the economic performance of the money that has been invested. The ROI is expressed as a percentage of the ratio between net profits, NP_{avg} to the TCI as in Equation (8).

$$ROI (\%) = \frac{NP_{avg}}{TCI} \times 100 \quad (8)$$

The profitability of the bio-refinery can be determined after the NPV, PBP, ROI, and IRR have been calculated. Table 6 summarizes the profitability indicators to decide whether the investment is acceptable or not. A positive NPV indicates that the earnings of the bio-refinery exceed the costs, and therefore, the bio-refinery is considered economically viable. Table 7 shows the selling price of pellet, fertilizer, xylitol, and bioethanol. The desired PBP of the investments should be under 5 years to be attractive [93]. The ROI and IRR should be more than the MARR set in this study to be profitable. The higher the ROI and IRR, the greater the returns exceed the capital cost [88].

Table 6. Profitability indicators of the bio-refinery.

Performance Criteria	Comments	Ref.
NPV	Acceptable if in positive value	[94]
PBP	Acceptable if in a short period of time	[88]
ROI	Higher than the MARR	[92]
IRR	Higher than the MARR	[88]

Table 7. Selling price of products.

Product	Cost (USD/ton)	Ref.
Pellet	90	[95]
Xylitol	5500	[96]
Bioethanol	963	[92]
Fertilizer	300	[97]

3. Results and Discussion

To examine the economic feasibility of the bio-refinery, three scenarios are evaluated in different settings. The scenario analysis is simulated based on the assumption that an existing pellet production plant's expansion produces higher-value products: xylitol and bioethanol.

Scenario 1: Economic analysis at different EFB splitting ratios to pellet production and xylitol and bioethanol production. In this scenario, the effect of EFB splitting ratios on the economic performance metrics is calculated to analyze the production process's viability.

Scenario 2: Sensitivity analysis at different EFB and product prices based on an EFB splitting ratio of 30% to pellet production and 70% to xylitol and bioethanol production. The purpose of the sensitivity analysis is to address the price fluctuations of EFB feedstock cost and market selling price of the pellet, xylitol, and bioethanol.

Scenario 3: Economic analysis of the coproduction of pellet with xylitol or pellet with bioethanol. The purpose of this analysis is to investigate whether the coproduction of pellets with xylitol or pellets with bioethanol is more economically feasible than the baseline scenario.

3.1. Profitability Analysis of Scenario 1

Figure 3 shows the profitability analysis of Scenario 1 at different EFB splitting ratios for pellet production and xylitol and bioethanol production, with a minimum acceptable return rate (MARR) of 16% and a 20-year life span. Both splitting ratios of 0% and 100% indicated that all EFB feedstock was fed into the production stream of xylitol/bioethanol and pellet, respectively. The splitting ratio of 0% had the highest net present value (NPV) of 129 million USD. Nevertheless, the NPV dropped drastically with the increase in the EFB splitting ratio to pellet production. In fact, the NPV plunged below zero at a splitting ratio of 80% and beyond and recovered slightly to the value of approximately 8 million USD at 100% EFB for pellet production only. In other words, for any EFB splitting ratio below 80%, the production of these three products is still feasible. The main reason for reducing NPV with the increase in EFB splitting ratio is the high total capital investment (TCI) and total production cost (TPC) of both xylitol and bioethanol processes that are not able to recover from revenue generation. It should be noted that xylitol products are the primary contributor to overall revenue because of their high market price of 5500 USD/ton [96]. As more EFB was diverted to the production of pellets, xylitol and bioethanol's capacity was subsequently reduced, which reduced the overall revenue. For every 10% increment in pellet production, the revenue is reduced by 19 million USD annually on average. By estimating from the slope in Figure 4, the reduction rate of revenue was much higher than TCI and TPC. The recovery of NPV to a positive value at 100% EFB for pellet production is

due to the exclusion of TCI and TPC of xylitol and bioethanol, which require expensive enzymes and yeast for production.

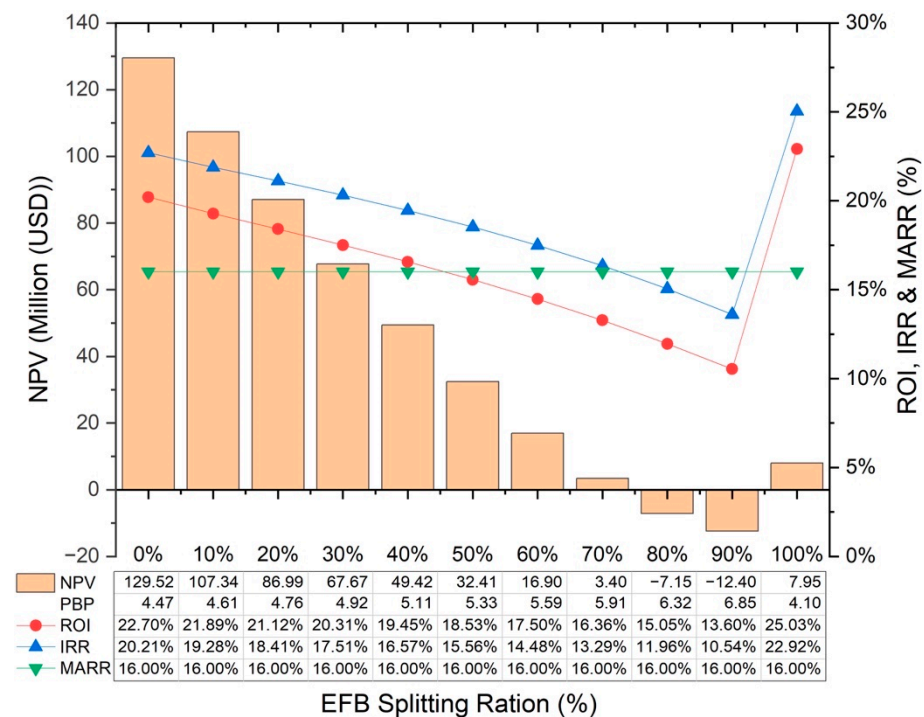


Figure 3. Economic profitability analysis at different EFB splitting ratios to pellet production.

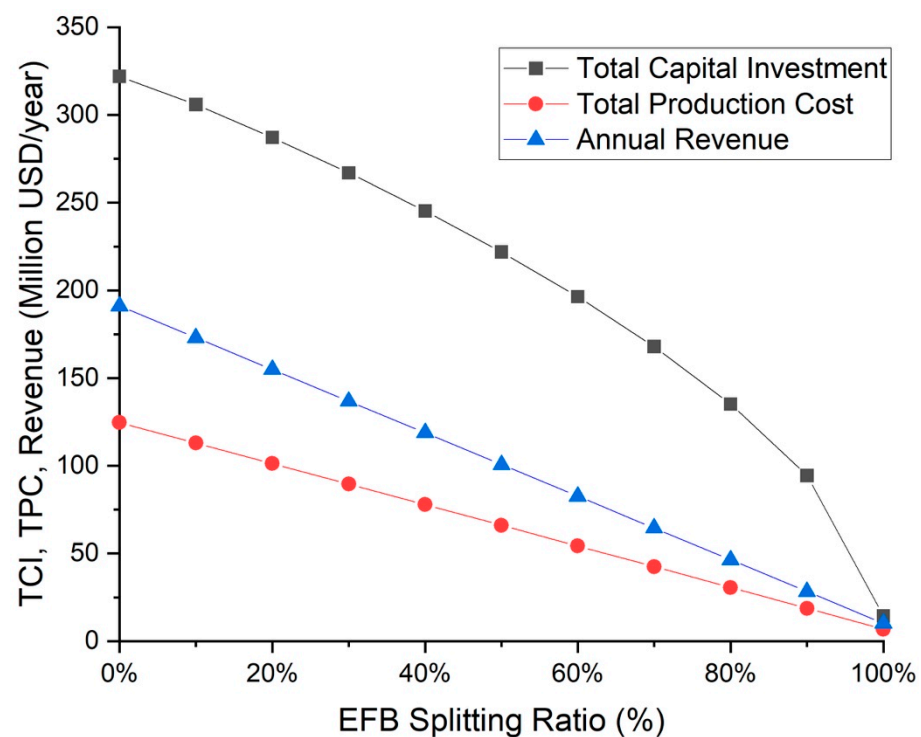


Figure 4. Changes in TCI, TPC, and annual revenue (at full capacity) at different EFB splitting ratios to pellet production.

On the other hand, the payback period (PBP) is an indicator of the length of time needed for the initial investment to break even or recover the investment cost; thus, a shorter PBP is preferred over a longer PBP. In this analysis, the payback period showed a

reversed trend of NPV, where the length of PBP increased gradually from 4.5 years (0% EFB splitting ratio) to 6.9 years (90% EFB splitting ratio) and decreased to 4.1 years at a 100% EFB splitting ratio. Typically, a PBP of less than or approximately five years is favorable [93]. Therefore, an EFB splitting ratio below 40% is justifiable. Similar to the NPV analysis, the TCI and TPC for pellet production only were 96% and 94% lower than those of xylitol and bioethanol production only, respectively. If all three products are to be considered in the production, TCI and TPC contributions by xylitol and bioethanol production will be significant. The unit operations involved in pellet production only consisted of a pretreatment reactor, dryer, and pelletization mill as the main process equipment. Those were less complex and less costly than the unit operations involved in xylitol and bioethanol production only, which consisted of a hydrolysis and fermentation reactor, activated carbon adsorption column, and distillation column. Moreover, the raw materials for xylitol and bioethanol production also involved the use of expensive enzymes (6310 USD/ton) [84] and yeast (5700 USD/ton) [84], as well as large amounts of sodium hydroxide and water, which have also contributed to a higher TPC.

Both return on investment (ROI) and internal return rate (IRR) values showed a similar reduction trend of NPV from the EFB splitting ratios from 0% to 90% but rebounded strongly to an ROI value of 23% and an IRR value of 25%, higher than that at the EFB splitting ratio of 0%. The difference between ROI and IRR is that IRR takes into account the time value of money by assuming the NPV equals 0 at the end of the 20-year life span; hence, the IRR values are slightly higher than the ROI values, which are in the range of 2% to 3%. The ROI and IRR were less favorable for the coproduction of xylitol and bioethanol than for pellet production only because the TCI and TPC of xylitol and bioethanol production were much more costly than those of pellet production. The ROI and IRR were then compared to MARR. It was found that the ROI and IRR of EFB splitting ratios below 40% and 70% were above 16%, respectively, which indicated that the investment was feasible and acceptable.

Comparing these four economic performance metrics, several possible production combinations were considerable, depending on the investor's interest and the demand for the products. For example, suppose the investor has an existing pellet production plant and would like to diversify some of the EFB feedstock to xylitol and bioethanol production. In that case, it is recommended that the EFB splitting to the existing pellet production should be 40% or less. The ROI and IRR of these options may seem lower than those of the existing pellet production plant. The NPV, which is the time value of money of cumulative cash flow, is at least one order of magnitude greater than that of the existing pellet production plant. Nonetheless, the tradeoff would be a slightly longer PBP as well as a higher TCI and TPC.

3.2. Profitability Analysis of Scenario 2

While the TCI requires a large lump sum at the beginning of the investment, it is usually a one-off contribution and is not affected by the global market supply chain. Both TPC and revenue contributed by the feedstock price and product selling price play a more important role during the operation lifetime. To understand the effect of the feedstock price and product selling price on the economic analysis, we performed a sensitivity analysis using the EFB splitting ratio of 30% to pellet production as a basis, where the corresponding prices and economic performance metrics are listed in Table 8.

Figure 5 shows the changes in economic performance metrics (NPV, PBP, ROI, and IRR) with EFB feedstock and product prices. Figure 5A shows that the feedstock price did not significantly impact the economic performance metrics. The price changes in EFB feedstock only affect the TPC. With a savings of 33% of the feedstock price (4 USD/ton), the NPV was improved by 5%, the PBP was reduced by less than 1%, and the ROI and IRR were improved by approximately 1%. In contrast, if the feedstock price was increased by 33% (8 USD/ton) and by 67% (10 USD/ton), the NPV was reduced by 5% and 10%, respectively. PBP length was increased slightly by 1% to 2%, while the ROI and IRR were reduced by less than 3%. In fact, an EFB price of 10 USD/ton still generated a positive NPV value, a PBP

period of 5 years was still acceptable, and both the ROI and IRR were still more significant than the MARR. The sensitivity analysis concluded that the contribution of EFB feedstock price to the total production cost is less significant.

Table 8. Baseline parameters and economic performance metrics at an EFB splitting ratio of 30% to pellet production.

Parameters	Baseline Data
NPV (Million USD)	67.67
PBP (years)	4.92
ROI (%)	17.51%
IRR (%)	20.31%
EFB Price (USD/ton)	6
Xylitol Price (USD/ton)	5500
Bioethanol Price (USD/ton)	963
Pellet Price (USD/ton)	90

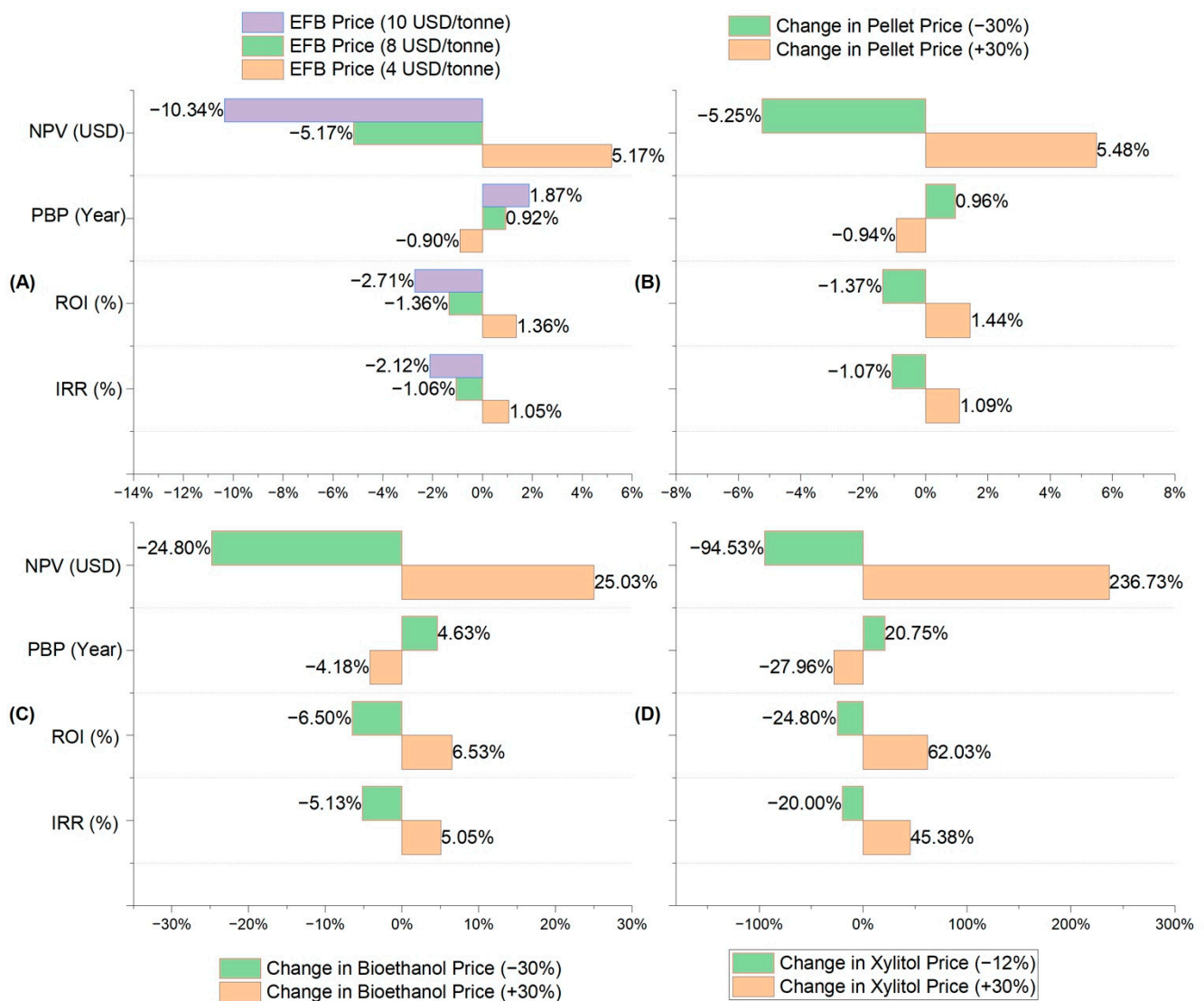


Figure 5. Sensitivity analysis of price changes in (A) EFB; (B) pellet; (C) bioethanol; and (D) xylitol at the basis of EFB splitting ratio of 30% to pellet production and MARR of 16%.

As shown in Figure 5B, the changes in the pellet price also indicate a relatively low impact on the economic performance metrics. When the pellet price (90 USD/ton) was

increased by 30%, the NPV, ROI, and IRR were increased by 5%, 1.4%, and 1.1%, respectively, while the PBP was reduced by less than 1%. Conversely, when the pellet's price was reduced by 30%, the NPV, ROI, IRR, and PBP showed their corresponding opposite values. The small changes in the economic performance metrics were partly due to the pellet's selling price being much lower than that of the other two products; hence, the contribution to the changes in revenue was negligible.

The changes in bioethanol price have a greater impact on the economic performance metrics, as shown in Figure 5C. An increase of 30% in bioethanol's price improved the NPV, ROI, and IRR by 25%, 6.5%, and 5.0%, respectively, and reduced the PBP by approximately 4.2%. A positive increase in the price of bioethanol is highly desirable to offset the expensive raw materials used in production, such as enzymes and yeast, and the large quantity of sodium hydroxide and water consumption in the delignification process.

The changes in xylitol price have the most significant effect on the economic performance metrics, as shown in Figure 5D. An increase in xylitol's price by 30% increased the NPV by 237%, improved the ROI and IRR by 62% and 45%, respectively, and shortened the PBP by 28%. Nevertheless, xylitol's lower boundary price could not be lower than 4802 USD/ton, approximately 12% lower than the benchmark price of 5500 USD/ton, to maintain a positive NPV. A 12% reduction in xylitol price shrank NPV, ROI, and IRR by 95%, 24.8%, and 20.0%, respectively, and increased the PBP by 20.8%.

In summary, there are three factors that contribute to an attractive economic performance: TCI, TPC, and revenue generation. Pricing sensitivity analysis has addressed the contributions of TPC and revenue generation to the economic performance metrics. It has been shown that the feasibility of coproduction of all three products (pellet, bioethanol, and xylitol) is highly dependent on the selling price of xylitol, which offers little room for price competition. Alternatively, one should forgo one of the products to further mitigate the risk and reduce TCI. This leads to the next scenario analysis, which is the coproduction of pellets with xylitol and the coproduction of pellets with bioethanol.

3.3. Profitability Analysis of Scenario 3

In Scenario 3, the economic performances of the coproduction of pellet with xylitol and coproduction of pellet with bioethanol were compared with the coproduction of pellet with xylitol and bioethanol on the basis of an EFB splitting ratio of 30% to pellet production at a MARR of 16%. The results are presented in Figure 6. Only the coproduction of pellet and xylitol is a feasible solution compared to the coproduction of pellet and bioethanol. On the other hand, the NPV of coproduction of pellets with xylitol was increased by 31%, while the PBP was reduced slightly to less than 4.5 years. The ROI and IRR of this combination were improved to 20% and 23%, respectively, above the MARR of 16%.

The coproduction of pellets and bioethanol was a no-go option due to its expensive pre-treatment process, low bioethanol yield, and selling price of bioethanol, which contributed to a negative NPV (Figure 6). From the simulation, the price of ethanol was required to be at least 1882 USD/ton to achieve a MARR of 16% or 1538 USD/ton at a lower MARR of 10%. This is consistent with Do et al. [98] on the limitation of bioethanol production from EFB. To further confirm bioethanol production's economic feasibility from EFB as a lignocellulosic source, a scenario of total conversion from EFB to bioethanol was further conducted. With the bioethanol production of 0.16 ton/ton of EFB, the production is only feasible with a bioethanol market price of 1758 USD/ton. This is in accord with the techno-economic analysis performed by Dávila et al. [75], which indicated that even with heat integration in the process that further reduced the production cost by 43%, the production price was still higher than the market price. This reflects the energy-intensive process with the heavy use of chemicals aside from the expensive enzymes for the purification and conversion involved in bioethanol production. This result also reflects that commercial production of bioethanol from lignocellulosic raw materials alone has not been widely implemented [30].

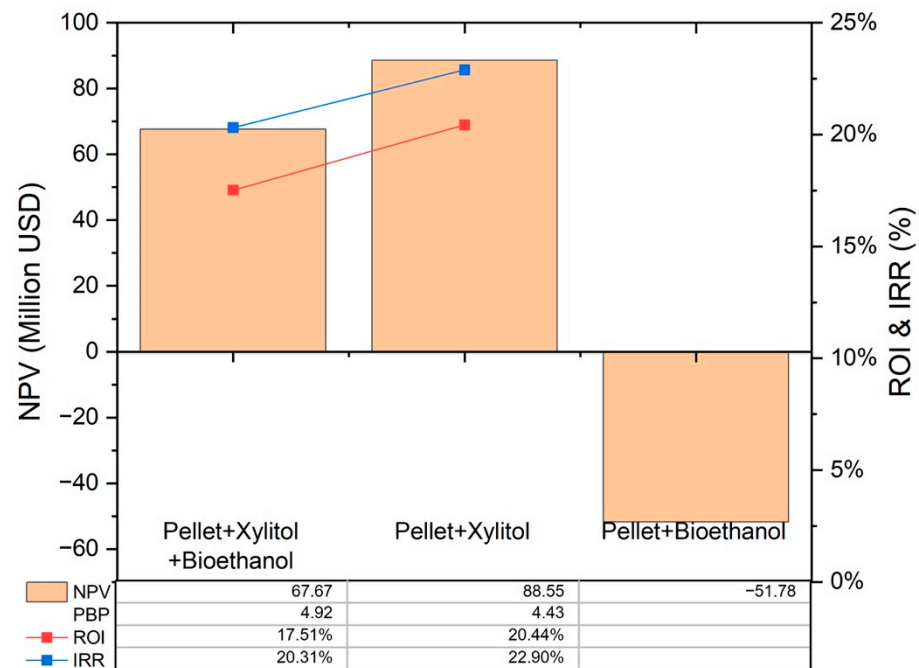


Figure 6. Economic profitability analysis of coproduction of pellet with xylitol and bioethanol, pellet with xylitol, and pellet with bioethanol at EFB splitting ratio of 30% to pellet production and MARR of 16%.

4. Conclusions

In this study, three scenarios were evaluated to determine the profitability of a bio-refinery producing pellet, xylitol, and bioethanol. The bio-refinery was found to be profitable at an EFB splitting ratio of below 40% for pellet production, resulting in a positive NPV, PBP lower than five years, and ROI and IRR higher than the MARR value of 16%. The results also showed that it is possible to produce both pellets and xylitol, which resulted in a higher NPV, shorter PBP, and higher ROI and IRR than the baseline scenario. The selling price of ethanol from either coproduction of pellets and bioethanol or bioethanol alone is still less competitive entering the market. Still, the coproduction of bioethanol with xylitol is feasible with a higher NPV than coproduction with pellets. Nevertheless, this work has successfully demonstrated that the valorization of EFB to high-value products is feasible.

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