Process design, simulation, and techno-economic analysis of integrated production of furfural and glucose derived from empty fruit bunches

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Abstract

This study proposes a new process design, simulation, and techno-economic analysis of an integrated process plant that produces glucose and furfural from Malaysian empty fruit bunches (EFB). An Aspen Plus-based simulation has been established to develop a process flow diagram of co-production of glucose and furfural along with the mass and energy balances. For the production capacity of 10 kilotons per year (ktpy) of glucose and 4.96 ktpy of furfural in Malaysia, purity of 98.21 and 99.54% - weight, respectively, was achieved. The plant's economics is analyzed by calculating the fixed capital income (FCI), operating costs, and working capital. In contrast, profitability is determined using cumulative cash flow (CCF), net present value (NPV), and internal rate of return (IRR). The FCI is calculated as Malaysian Ringgit (MYR) 81.61 million, while the working and operating expenses are calculated as MYR 11.29 million and MYR 46.92 million, respectively. This project achieves MYR 31.45 million as NPV with a positive IRR of 14.25% and return on investment (ROI) of 22.06%. As a result, a profitable integrated process plant is established with future upscaling parameters and key cost drivers. The proposed integrated process plant minimizes waste generated from the palm oil mill, resulting in a profitable and sustainable plant.

1. Introduction

The usage of natural resources has spiked up rapidly due to the tremendous increase in the global population. The vast number of resources consumed generally results in more waste. It is anticipated that by 2050, worldwide municipal solid waste (MSW) will be over 3.40 billion metric tonnes (MT) (Ellis, 2018). Food waste dominated the highest percentage, followed by paper and paperboard, plastic, yard trimmings, and metals (The World Bank, 2021). These wastes are usually disposed of in landfills but may be recycled, composted, or utilized in energy recovery.

Malaysia, Indonesia, and Thailand are the leading producers of palm oil, accounting for more than 90% of the global market in total, with Malaysia accounting for 25.9% of global production and 33.7% of global palm oil exports in 2019 (MPCO, 2021; Zafar, 2021). In palm oil plantations, fresh fruit bunch is employed as a raw material; however, only 23% of the raw material is utilized to make palm oil, with the remainder being trash **(Aziz et al., 2015)**. Most waste landfills are located far from cities. Therefore, a high operating cost for waste transportation and disposal is associated with palm oil wastes, including empty fruit bunch (EFB), fibers, and nutshells **(Aziz et al., 2015)**. In certain scenarios, open-ended burning is used to dispose of EFB trash, causing huge environmental difficulties, including global warming potential (GWP) and air pollution (Ninduangdee and Kuprianov, 2016). These EFB may also be reused as biomass, reducing the processing plant's economic and environmental burdens. Since EFB biomass is low in sulphur, it reduces GWP and air pollution (Ninduangdee and Kuprianov, 2016). Furthermore, EFB may be processed into high-value products such as glucose, xylitol, levulinic acid, and vanillin (Hafyan et al., 2020). In addition, it may be chemically processed into ethanol, furfural, and lactic acid and converted into energy such as bio-oil, biogas, bioethanol, and methane (Geng, 2013).

Malaysia, Indonesia, and Thailand generated 27 million MT of EFB in 2019 (Zafar, 2021). Since EFB is readily available in Malaysia, it is an inexpensive renewable energy source (Alaw and Sulaiman, 2019). These EFB may be further processed to extract valuable food and chemicals; hence, promoting resource conservation and sustainable processes (Alaw and Sulaiman, 2019). However, there is still much waste to date, even if many plants use the EFB to manufacture foods, chemicals, or energy. This is because the existing process plant only valorizes a particular component in EFB such as cellulose or hemicellulose only. This procedure also requires many separations, increasing the capital cost. To overcome this, lignocellulosic biomass may be processed into numerous products in a single plant in an integrated way. For an integrated process plant producing both food and chemicals, glucose and furfural are selected as end products because they may be produced in a single facility with minimal equipment. Moreover, the residual lignin may be used as a fuel for boilers to supply heat energy. Hence, the plant's economic and environmental impacts are reduced as a result of maximizing EFB's potential.

Currently, only a few studies have worked on an integrated process plant employing EFB, where theoretical data is used to generate findings. Ajiwibowo et al. (2019) developed an integrated system to convert EFB to hydrogen and ammonia. Although their system can produce hydrogen and ammonia efficiently, their study only focused on energy analysis, without sufficient techno-economic analysis. In addition, an ethanol production system using EFB as feedstock has been developed and analyzed by Piarpuzán et al. (2011). Their work did not focus on developing an integrated system. Vargas-Mira et al. (2019) have compared and evaluated different routes of conversion technologies for hydrogen production from EFB.

On the other hand, Contreras-Zarazúa et al. (2022) have proposed furfural production utilizing agricultural residues. Their techno-economic analysis showed that furfural production from wheat straw through combined dilute acid pretreatment and thermally coupled distillation led to the lowest cost and environmental impacts. Furthermore, Hossain et al. (2019) have proposed a co-production system for bioethanol and furfural from corn stover, combining both biochemical and thermal pretreatment. Heat integration has been conducted, and the system showed feasible economic profitability. Unfortunately, those previous studies are not solely dedicated to converting EFB to glucose and furfural. Also, the process conditions were not optimized to maximize the production rate and purity. Existing research also lacks modelling data and production rates for integrated processes. The process design and optimization may also assist in achieving the requisite product purity. In addition, existing work lacks economic analysis and profitability to assess an integrated plant's viability. Therefore, this work aims to use simulation to obtain the mass and energy balance for optimizing the integrated process and perform an economic analysis to identify the overall profitability and plant viability.

Converting EFB components into value-added products reduces waste generation and promotes a circular economy. Using process simulation of Aspen Plus (Aspen Technology Inc.), the production rate, purity, and flowrate of the product may be calculated and adjusted to reduce raw material consumption and eventually reduce the capital cost. When evaluating the profitability of the integrated plant, it helps to compare the main cost drivers of the integrated plant. Furthermore, sensitivity analyses may optimize

production parameters such as capacity and fixed capital. Overall, the plant viability can be determined by the process sustainability and profitability.

2. Methodology

2.1 Process description

2.1.1 Raw material and products

2.1.1.1 Empty fruit bunch

EFB is lignocellulosic biomass composed of cellulose, hemicellulose, and lignin where it can be broken down into simple sugars to produce various food additives (Geng, 2013). On the other hand, this biomass can also be converted to renewable energy such as syngas, ethanol, furfural, and bio-oil through thermochemical or biological conversion (Geng, 2013).

Table 1
Composition of EFB (wt.%) (Reproduced from the work of Chiesa and Gnansounou (2014)).

Components	Sub-Components	Percentage (wt.%)
Cellulose	Glucan	29.60
Hemicellulose	Xylan	20.80
	Acetyl group	1.50
Lignin	Acid insoluble Lignin	20.70
	Acid soluble Lignin	2.20
Others	Ash	5.40
	Water	19.80

2.1.1.2 Furfural

Furfural is an oily, colorless liquid that turns dark brown when exposed to air (Ebert, 2008). It is used to refine lubricating oil, as a fungicide in tetrahydrofuran manufacturing, and as an industrial solvent (Ebert, 2008). Moreover, it is an important raw material for the production of furfuryl alcohol by catalytic hydrogenation and is also used for other transportation fuels like ethyl levulinate and dimethylfuran (Mordor Intelligence, 2021; Ebert, 2008). Furfural is produced at high purity with low moisture content by dehydration of 5-carbon sugar xylose and arabinose (Ebert, 2008). Table 2 provides its specifications.

Table 2
Properties and composition of furfural (Reproduced from the work of **Hongye Holding Group Corporation Ltd. (2020)**).

Components	Value	Units
Purity	98.5	wt.%
Moisture	0.2	wt.%
Acid mol/L	0.016	%

In 2018, worldwide furfural exports and imports increased to 146.7 and 155.7 kilotons per year (ktpy), respectively (UN Data, 2018). In Malaysia, the import demand for furfural reached 267.8 tpy in 2018 (UN Data, 2018), and this value is expected to with a compound annual growth rate (CARG) of 5% by 2026 (Mordor Intelligence, 2021). Among the global consumers, China is the largest consumer globally, followed by western Europe and other Asian countries (IHS Markit, 2020).

2.1.1.3 Glucose

Glucose is a viscous, colorless, and sweet fluid that improves the food texture, taste, and gloss (Wilson and Lilly, 1969). Therefore, it is often used as a sweetener in the production of food and chemicals industries (Basso and Serban, 2020). Glucose can also be converted into bioethanol through fermentation with yeast, producing bioenergy, or into levulinic acid, succinic acid, lactic acid, etc. (Hafyan et al., 2020). Industrial glucose production comes in various compositions and purity, which can be benchmarked by their dextrose equivalent (DE) value, which measures the percentage of invert sugar, including glucose, oligomer, dextrose, and maltose (Sarungalo, 2005). The sweetness of glucose syrup is determined by the feedstock's DE content, including low DE (26–29%), high DE (40–45%), and the sweetest DE (56–64%) (Sarungalo, 2005). For EFB, the DE falls between 42 and 45%, and the composition is shown in Table 3 (21Food, 2021).

Table 3
Properties and composition of glucose (Reproduced from the work of 21Food (2021)).

Components	Value	Units
Dry Solids	80.0–84.0	wt.%
Moisture	16.0–20.0	wt.%
Dextrose Equivalent (DE)	42.0–45.0	%
Sulfate Ash	0.4	wt.% max
SO_2	200	ppm
pH	4.0–6.0	pH

In 2018, worldwide glucose exports and imports increased to 2995.5 and 3773.3 ktpy, respectively (UN Data, 2018). In Malaysia, the import demand for glucose reached 44.46 tpy in 2018 (UN Data, 2018), and this value is expected to be double by 2030, with a compound annual growth rate (CARG) of 5.2% (Persistence Market Research, 2020). Belgium is the worlds' largest consumer, whereas Malaysia stands at 13th place (UN Data, 2018).

2.1.2 Process flowsheet of the integrated process

The glucose and furfural are produced *via* enzymatic hydrolysis and dehydration, respectively. The process includes breaking down the EFB to separate cellulose and hemicellulose in feed preparation. Furthermore, it is followed by enzymatic hydrolysis for glucose production and dehydration for furfural synthesis along with purification and recovery of the products to achieve the desired specification. Figure 1 shows the associated process description of each unit. The detailed process flow diagrams of the integrated production, including legend as well as mass and energy balance table (MEBT) are depicted in Supplementary Information (Section A).

2.1.2.1 Feed Preparation

The EFB is purchased from the palm oil processing plant and stored in a warehouse before being conveyed to the feed preparation. Initially, the EFB contains 19.8 wt.% moisture, which is reduced to 10 wt.% using 105°C hot air in the rotary dryer (S-1001) (Loh, 2018). Then, the dried EFB is transported to a grinder (S-1002) to be cut into small pieces with a size between 0.1 to 1 mm (Kenthorai Raman and Gnansounou, 2015). Furthermore, it is transported to a vibrating screen (S-1003), which contains an 80–20 wired mesh to separate the smaller particles sized below 1 mm. In contrast, the larger particles are recycled back to the grinder (S-1002) to obtain uniformly sized EFB (Kenthorai Raman and Gnansounou, 2015).

2.1.2.2 Pretreatment

In the pretreatment section, process water and 70 wt.% dilute sulfuric acid are pumped from its storage tank to an agitated mixing tank (M-1101) operating at 30°C and 1 atm. Simultaneously, the recycled water from the furfural purification unit (C-1302) is pumped to the mixing tank (M-1101). Here, the sulfuric acid is diluted using the process and recycled water, and then mixed with the ground EFB from the feed preparation unit (CONV-1101) in an agitated mixing tank (M-1102). The flowrate of sulfuric acid and process water is adjusted to 30% of solid loading with 18 mg of sulfuric acid per g of dry EFB (Humbird et al., 2011). The mixture is then pumped (P-1104) to 6 atm and heated (E-1101) to 158°C before being fed into an insulated continuous stirred tank reactor (CSTR) (R-1101) and stirred for 5 min (Humbird et al., 2011). The reactor converts most hemicellulose to xylose, with secondary reactions as shown in Table 4.

Table 4
Reaction and its conversion in CSTR (R-1101).

Components	Reactant	Reaction	Conversion
Cellulose	Glucan	$(Glucan)_n + n\ H_2O$ ◊ n Glucose	10.30%
Hemicellulose	Xylan	$(Xylan)_n + n\ H_2O$ ◊ n Xylose	97.40%
	Xylose	Xylose ◊ Furfural + 3 H_2O	5.00%
Lignin	Lignin	$(Lignin)_n$ ◊ n Soluble Lignin	5.00%
Others	Acetate	Acetate ◊ Acetic Acid	100.00%

The product from CSTR (R-1101) is cooled (E-1102) to 50°C for solid separation. The cooled product is sent to a decanter centrifuge (S-1101) to separate solid and liquid. The decanter centrifuge can separate particles sized from 0.1 to 1 mm using its centrifugal force rotating horizontally, separating the solids on the separator wall, and removing them using a screw conveyor (Dolphin Centrifuge, 2021). The solid is completely removed with 5 wt.% moisture and sent to the neutralization unit, while the liquid stream is sent to the dehydration unit.

2.1.2.3 Furfural synthesis

The liquid stream from the pretreatment is dehydrated to convert xylose into furfural, where the reaction is autocatalyzed by heat. Firstly, the liquid is heated to 170°C and pumped (P-1201) to 8.8 atm into an insulated CSTR (R-1201) (Mittal et al., 2017). The residence time of the reaction is 20 min. As our processing plant is continuous, the CSTR (R-1201) has a 3.62 m^3 capacity, accounting for the residence time. The reactors were assumed to have a maximum operating capacity of 80% of the designed volume (Mittal et al., 2017). In CSTR (R-1201), the conversion of xylose into furfural can be achieved up to 96.50% (Mittal et al., 2017).

2.1.2.4 Furfural recovery

The furfural mixture from the dehydration unit requires further purification because it contains water, sulfuric acid, and acetic acid, which must be removed to obtain high purity of furfural. Initially, the condensed liquid from the dehydration unit is fed into a distillation column (C-1301), where furfural and water are recovered as distillate (top) and the bottom stream, which contain diluted acid from the distillation column. The bottom stream is directed to the wastewater treatment unit. Meanwhile, the distillate is cooled (E-1303) to 40°C before it is diverted to a liquid-liquid extraction column (C-1302), where butyl chlorine is introduced as a solvent to break up the azeotrope of furfural and water (Nhien et al., 2021). Fresh butyl chloride from its storage tank is mixed with the recycled butyl chloride from the distillation column (C-1303) in a mixer (M-1301) and heated (E-1304) to 40°C (Nhien et al., 2021). The heated solvent is fed to the extraction column (C-1302), where the water is separated in the bottom stream, recycled to the pretreatment unit, and 5 wt.% of water is purged to avoid accumulation in the

production system (Nhien et al., 2021). The furfural-butyl chloride stream from the top is sent to the second distillation column (C-1303) for solvent recovery (Nhien et al., 2021). The furfural-butyl chloride mixture is separated using a distillation column (C-1303), where the purity of furfural is achieved to a value of 99.54 wt.%. The purified furfural (bottom) is cooled to 30°C, which is then transported to the storage tank; the remaining solvent is left as a distillate from the distillation column for recycling.

2.1.2.5 Glucose synthesis

Glucose synthesis is separated into two units, i.e., neutralization and saccharification units. The wet solid stream from pretreatment is fed into an agitated mixing tank (M-1402). The diluted base (neutralizing liquid), which contains 50 wt.% of sodium hydroxide, process water, and the recycled water from the glucose purification unit (C-1601), are pre-mixed in an agitated mixing tank (M-1401) before being further mixed in M-1402 (Humbird et al., 2011). The flowrate of sodium hydroxide is fed such that it is equimolar to the moles of sulfuric acid and acetic acid in a wet solid stream while the process water flowrate is adjusted to account for 20% solid loading in M-1402 (Humbird et al., 2011). To account for complete neutralization of acetic acid, sodium hydroxide is fed 10 mol.% in excess (Humbird et al., 2011). In this reaction, sulfuric acid and acetic acid are converted into sodium-based salt (e.g., sodium sulfate and sodium acetate). After neutralization of acids, the pH of the slurry is increased to pH 5, and it is further heated (E-1401) to 48°C (Humbird et al., 2011).

In the saccharification unit, the heated slurry from the neutralization unit is fed into an insulated CSTR (R-1501), which operates at 48°C and 1 atm (Humbird et al., 2011). Cellulase enzyme from its storage tank is fed into the CSTR (R-1501) (Humbird et al., 2011). With enzymatic hydrolysis, 95.20 wt.% of the cellulose is converted into glucose (Humbird et al., 2011). The residence time of the reaction is two successive days (48 h). The slurry from CSTR (R-1501) is pumped into a decanter centrifuge where all the solids that contain 5 wt.% moisture are removed and sent to the boiler feed unit as fuel stock while the liquid stream is sent to the final stage for glucose purification.

2.1.2.6 Glucose recovery

The glucose mixture from the saccharification unit contains glucose, water, and other impurities. For glucose purification, the glucose mixture from the saccharification unit is fed into a distillation column (C-1601), where most glucose can be separated in the bottom stream. The distillation column contains four stages with a reflux ratio of 1, and the feed is at the second stage from the top. This separation method increases glucose purity to 96.67 wt.%. The remaining water is removed as a distillate from the distillation column and chilled (E-1603) to 30°C before being recycled to the neutralization unit with a 5% purge rate. Finally, the glucose stream is cooled (E-1604) to 30°C and pumped to the glucose storage tank.

3. Results And Discussion

3.1 Process simulation

Aspen Plus features a variety of modules and thermodynamic databases for simulating chemical processes. Therefore, the integrated process of glucose and furfural production from EFB (Fig. 2) is simulated using Aspen Plus V10, with the process conditions obtained from the literature review (Dolphin Centrifuge, 2021; Humbird et al., 2011; Kenthorai Raman and Gnansounou, 2015; Loh, 2018; Mittal et al., 2017; Nhien et al., 2021). Here, the feed preparation unit in Fig. 2 is not included in the process simulation since Aspen Plus limits the usage of solid handling and batch processes. Therefore, it is assumed that the EFB is dried and ground. In some major unit-operation, there is a lack of information on equipment design and operating parameters. Hence, the following assumptions are made in the present work:

- The process is continuous and in a steady state.
- There is no loss of pressure and temperature across equipment and pipelines.
- All transfer pumps increase by 0.1 atm to compensate for pressure loss in the pipeline.
- Positive displacement pumps are used for streams with a capacity lower than 0.55 m3/h and streams with solid-liquid slurry (Liquiflo, 2016), while others rely on centrifugal pumps (Liquiflo, 2016).

3.1.1 Set up of Aspen simulation

3.1.1.1 Property Method

This study employed NRTL as the thermodynamic property package, which is identical to the existing studies in literature (Humbird et al., 2011). However, the binary interaction between certain components such as butyl chloride and furfural was not included in the NRTL; therefore, UNIQUAC property package can be used for vapor-liquid equilibrium (VLE) as well as liquid-liquid extraction (LLE) (Manual, 2001). Thus, NRTL is chosen as the base property method while UNIQUAC property method is added to the referenced method in Aspen Plus.

3.1.1.2 Defining Components

All liquid components are available in the Aspen database. However, the solid component, i.e., EFB; however, is not available in the Aspen database. Therefore, it has to be added manually by defining the corresponding properties such as molecular weight, solid enthalpy of formation, solid molar volume (VSPOLY-1), and solid head capacity (CPSPO1-1). This information of which can be .obtained from the literature (Wooley and Putsche, 1996). The details of the equipment block selection are made available in Supplementary Information (Section B).

3.1.2 Sensitivity analyses

Sensitivity analyses are conducted to maximize the yield and purity of furfural and glucose in the product purification units. The influence of 4 manipulated variables is examined in order to determine the optimum operating conditions. Two-point values are applied to examine the influence of the higher and lower bounds on the parameters to which the yield and purity of products are most sensitive. As Aspen

Plus has calculated the binary interaction between the molecules, the reflux ratio, and a number of stages in the distillation column are varied to compare the purity and flowrate of the product. In addition, a solvent used in the liquid-liquid extraction column and the purge percentage of both recycled streams are varied to determine the most suitable recycle flowrate and save cost.

3.1.2.1 Number of stages

Figure 3 shows the product composition in the distillation columns 1 to 3 and the liquid-liquid extraction column. The number of stages of distillation columns 1 and 2 is varied from 5 to 15. Based on Fig. 3, distillation column 1 gives the highest purity and flowrate of furfural at Stage 10th ; distillation column 2 achieves the maximum purity and flowrate of furfural at Stage 13th. On the other hand, the number of stages of the final distillation column ranges from 2 to 10. The maximum flowrate and purity of glucose were found to be 34.862 kg/h and 98.18 wt.%, respectively, at the 3rd stage before the flowrate and purity declined slightly to 34.86 kg/h and 98.15 wt.%, respectively. For the LLE column, the optimum stage was found to be the 7th stage. From Fig. 3, it is apparent that the number of stages only provides a marginal effect on the furfural flowrate and purity. Therefore, it is not recommended to increase the number of stages as the marginal increase in the furfural flowrate and purity were achieved at the expense of an increase in the column capital cost.

3.1.2.2 Reflux Ratio

Figure 4 shows the effect of the reflux ratio on the composition and yield of products. The reflux ratio in all three distillation columns was varied from 0.7 to 1.5. Based on Fig. 4, distillation column 1 gives the highest purity and flowrate of furfural at a 1.5 reflux ratio. For distillation column 2, the optimum reflux ratio is observed at the intersection point between both lines, which is 0.9. For distillation column 3, the increase in reflux ratio has no significant effect on the flowrate and purity of products; thus, original reflux ratio of 1 is used. Overall, the optimal reflux ratio is recorded at 1.5 for distillation column 1 and 0.9 for distillation column 2. Meanwhile, the reflux ratio of distillation column 3 remains at 1, based on the original literature review data (Nhien et al., 2021).

3.1.2.3 Solvent type

The type of solvent is analyzed in a liquid-liquid extraction column (C-1302) between butyl chloride and toluene. According to Nhien et al. (2021), the feed-to-solvent ratio for furfural is lower for toluene at 2.68, whereas butyl chloride has a feed-to-solvent ratio of 7.68. From process simulation using Aspen Plus, the purity and flowrate of furfural were studied for both solvents, and the result is recorded in Table 5. Based on the table, butyl chloride and toluene solvents produce similar furfural purity (99.98 and 99.50 wt.%, respectively) and flowrate (17.20 and 17.27 kg/h, respectively). Thus, both are promising solvents, and a literature review is performed to select the most suitable solvent. Although a higher amount of butyl chloride is needed, as mentioned previously, the amount of energy required in the butyl chloride case is less than that in the toluene case (Nhien et al., 2017). With this regard, Nhien et al. showed that butyl

chloride is the best solvent for the furfural manufacturing process, saving 44.7% of the total annual cost while lowering CO_2 emissions by 45.5%, in comparison to using toluene and benzene as solvents. Therefore, the plant expenses can be saved. The selling price of furfural can be increased due to its higher grade and purity when butyl chloride is selected as a solvent in the furfural production unit.

Table 5
Furfural purity and flowrate from Aspen Plus simulation for two solvents.

Solvent	Furfural purity (wt.%)	Furfural flowrate (kg/h)
Toluene	99.50	17.29
Butyl Chloride	99.98	17.20

3.1.2.4 Recycle flow rate

To avoid the accumulation of undesirable chemicals in the process as a result of recycling, some parts of the recycling streams are purged before being recycled back into the process. In this sensitivity analysis, the first recycle stream (Recycle 1) consists of 99.5 wt.% water, 0.3 wt.% acetic acid, 0.1 wt.% butyl chloride, and 0.1 wt.% furfural, while the second recycle stream (Recycle 2) mainly consists of water (99.9 wt.%) with 0.1 wt.% of furfural as an impurity. Figure 5 shows the effect of purge fraction on the flowrate and purity of products. The purge percentage for both Recycle 1 and 2 is varied from 0–10%. The first recycle stream with 99.5 wt.% of water recycled back into pretreatment unit achieves the optimum flowrate and purity of furfural (17.53 kg/h and 99.54 wt.%, respectively) at a 5% purge percentage. Based on Fig. 5, the flowrate of the furfural is inversely proportional to the purge percentage, while the purity of the furfural is directly proportional to the purge percentage. In this aspect, decreasing the mass flowrate of recycling streams may improve the purity of furfural. Due to minor improvement in flowrate and a slight decrease in purity of furfural, the optimum purge percentage is recorded at the intersection point between both lines. The second recycling stream that recycles 99.9 wt.% of water back to the neutralization unit, has an optimum glucose purity and flow rate (34.86 kg/h and 98.25 wt.%) at a purge percentage of 10%. In this case, the purge fraction has no significant effect on the glucose flow rate while the purity of the glucose increases with increasing purge percentage. Overall, 95% and 90% of water is recovered and recycled back to the pretreatment and neutralization units for reuse purposes, respectively.

3.1.3 Simulation Results

The optimization results are recorded in Table 6. Based on the integrated process of glucose and furfural production from EFB, the desired final product purity is obtained using a basis of 100 kg/h of dry EFB. After optimization, the final purity and flowrate of the product are achieved with the absence of cellulase enzymes in the final product. Further, the process is optimized by changing the equipment design based on optimum operating conditions to maximize the purity and flowrate of final products. Therefore, optimized simulation attains better plant efficiency and minimizes waste produced. After optimization, the mass flowrate is scaled by adjusting the feedstock (dry EFB) to attain the annual plant capacity (i.e.,

10 ktpy of glucose and 4.96 ktpy of furfural), where the plant can achieve a purity of 98.21% for glucose and 99.54% for furfural.

Table 6
Final product purity and flowrate from Aspen Plus simulation after optimization.

Product	Purity (wt.%)	Flowrate (kg/h)	Yield (%)
Glucose	98.21	34.86	94.45
Furfural	99.54	17.53	67.59

3.2 Economic analysis

For economic analysis, the total capital investment is calculated using all the equipment costs according to its capacities and flowrate of feedstock, product, and utility cost. The summary of feedstock, product, and utilities is shown in Table 7.

Table 7
Feedstock, product, and utility flowrate.

Feed stream		**Product stream**	
Feedstock	**Flowrate (kg/h)**	**Product**	**Flowrate (kg/h)**
EFB	4435.10	Glucose	1262.63
Sulfuric acid	91.46	Furfural	626.34
Process water	1560.10	Lignin	1402.42
Butyl chloride	2.44	Wastewater	2318.05
Sodium hydroxide	3.23		
Cellulase enzyme	23.55		
Utility stream			
Utility	**Description**	**Value**	**Unit**
Hot Air	5% relative humidity, 105°C	19762.24	kg/h
Cooling Water	30°C	1446933.58	kg/h
Hot Water	80°C	5840.99	kg/h
Low-Pressure Steam	3 bar saturated vapor	15001.77	kg/h
High-Pressure Steam	20 bar saturated vapor	31230.91	kg/h
Electricity	unit	177.02	kWh/h

3.2.1 Fixed capital investment

Fixed capital investment (FCI) is calculated to build a new plant, including the building, construction, and equipment costs required. The fixed capital is calculated using equipment price from 2006 and 2002 adjusted to inflation and location (Peters et al., 2003; Sinnott and Towler, 2020). The total fixed capital investment was found to be Malaysian Ringgit (MYR) 81.61 million. Among them, inside battery limit (IBL) cost alone covers 48% of the FCI as the plant uses various types and numbers of equipment.

Table 8
Total fixed capital summary.

Fixed Capital Cost (FCI)	Cost (million MYR)
Total IBL cost	39.17
Total OBL cost	19.18
Indirect cost	23.26
Total FCI	**81.61**

3.2.1.1 Direct cost and Indirect cost

Direct cost can be divided into IBL and outside battery limit (OBL). IBL is the total cost of purchasing and installing all process equipment inside the process boundary; OBL is the total cost required for building and yard improvements along with the construction and installation of utility systems, storage, and waste treatment systems that are outside the process boundary.

IBL costs are adjusted along with installation, electrical system, control system, phase handle, and piping cost within the process boundary. The cost of equipment is determined from Chemical Engineering Design by Gavin and Sinnott at U.S. Gulf in 2006 and Plant Design and Economics for Chemical Engineers by Peters in the USA in 2002 (Peters et al., 2003; Sinnott and Towler, 2020). Finally, the cost of each piece of equipment can be calculated by adjusting the location factor to Malaysia, cost indices to 2020, and its lang factor accordingly. Converting the total cost to MYR as in May 2021 with an exchange rate of USD is 4.12 MYR **(XE, Currency, 2021)**. The total cost of IBL is calculated as MYR 39.17 million (see Supplementary Information, Section C.1). The major cost driver of direct cost is the saccharification unit which takes 41.8% (MYR 16.37 million) of IBL cost. This is because eight reactors are used for higher conversion into furfural using cellulase enzyme. Other than a reactor, a distillation column has a higher price in purification units.

Table 9
Total equipment cost summary.

Unit	Cost (million MYR)	Percentage of IBL
Feed preparation unit	7.30	18.62%
Pretreatment unit	2.58	6.60%
Dehydration unit	1.89	4.83%
Glucose purification unit	7.61	19.42%
Neutralization unit	0.80	2.05%
Saccharification unit	16.37	41.80%
Furfural purification unit	2.61	6.67%
Total equipment cost	**39.17**	**100.00%**

OBL cost is identified for each facility which is estimated at a percent of FCI (Peters et al., 2003). These general facilities include buildings, yard improvements, communication, sanitary disposal, and safety installation follow similar factors as well. The total cost of OBL was calculated as MYR 19.18 million (see Supplementary Information, Section C.2). On the other hand, indirect costs include legal expenses, construction costs, and contractor fees, and the cost estimation is similar to the OBL cost (Peters et al., 2003). Overall, the total indirect cost is calculated as MYR 23.26 million (see Supplementary Information, Section C.3).

3.2.2 Operating cost

Operating costs comprise both the manufacturing and non-manufacturing costs of the plant. The manufacturing costs comprise variable and fixed costs, where variable cost includes labor wages, maintenance costs, insurance, and interest, and fixed cost includes raw materials and utility costs incurred annually (Malaysia Indeed 2021; Peters et al., 2003). Non-manufacturing cost includes administration, research, and development, as well as distribution and marketing. The annual operating capital is calculated as MYR 46.92 million (see Supplementary information, Section D). In the plant, cellulase enzyme has contributed 85.53% (MYR 11.49 million) of feedstock cost due to the high cost of cellulase and the absence of an enzyme recovery unit. Nonetheless, employing cellulase improves the conversion of furfural and eventually resulting in higher profits.

Table 10
Operating cost summary.

Operating Cost	Cost (million MYR/y)
Feedstock	13.47
Utilities	3.25
Process labor cost	0.92
Maintenance cost	5.71
Operating supplies	0.86
Plant overhead	4.50
Insurance and interest	4.90
Depreciation cost	11.35
Non-manufacturing cost	1.96
Total operating cost	**46.91**

3.2.3 Working capital

Working capital is the money needed to start up and run a plant until it generates enough revenue to pay off debt and purchase inventory (Sinnott and Towler, 2020). The raw materials and final products stock have three weeks inventory, and water has one week inventory as it is easily available (Sinnott and Towler, 2020). It is assumed that six weeks inventory value is allocated to both debtors and creditors. The working capital is calculated as MYR 11.29 million with the previous inventories (see Supplementary information, Section E).

Table 11
Working capital summary.

Working Capital	Cost (million MYR)
Feedstock inventory	0.86
Product inventory	4.17
Debtor amount	8.33
Creditor amount	2.06
Total working capital	**11.29**

3.2.4 Profitability evaluation

3.2.4.1 Cumulative cash flow

The production plant runs for 20 years in Malaysia, with an additional year for planning and design in 2021, two years for building and installation, and one year for decommissioning in the final year (2044). It is assumed that 70% of the total working capital is used in that year, and 15% of total working capital is shared equally in the following years as the growth rate in production is linear. With a declining balance, the fixed capital begins to depreciate at a rate of 13.91% (see Supplementary information, Section F.1). In Malaysia, a company that has a fixed capital of above MYR 2.5 million pays a 24% corporate tax (LHDN Malaysia, 2020). The impact of inflation during the lifetime of plant operation is estimated to be negligible. Figure 6 shows the plant recovering full FCI at the initial stage of the 9th year and profiting until the 22nd operating year. The remaining residual value and working capital are anticipated to be recovered at the end of the project. Overall, CCF is provided in the Supplementary Information (Section F.2).

3.2.4.2 Net Present Value, Internal Rate of Return and Return on Investment

The discounted cash flow after tax is used to compute this project's net present value (NPV). The discount rate is assumed to be 10% as the source of funds between equity and loan is uncertain at this stage of the project. Based on the assumptions, the NPV is calculated as MYR 31.45 million (see Supplementary Information, Section G). The discount rate that gives a zero NPV is the internal rate of return (IRR). Figure 10 shows a graph of NPVs against a range of discount rates where the IRR value is calculated to be 14.25%. Moreover, the return on investment (ROI) is determined using the annual operating profit and total investment, which is calculated to be 22.06%.

3.2.4.3 Sensitivity analysis

Using the cumulative cash flow (CCF) table, the various parameters affecting the profitability of the plant can be varied to calculate the change in NPV and IRR. With a positive IRR, the NPV of the plant increases, thus increasing its profit. On the other hand, negative NPV and IRR indicated a decrease in plant profit. This parametric change must be avoided to maintain the profitability of the plant.

The tornado chart shows that capacity is the major cost driver and cutting capacity by 20% dramatically reduces the NPV and IRR. To make a plant profitable, its capacity should be expanded or maintained. Aside from capacity, the selling price of furfural significantly influences NPV and IRR. From the market analysis, the furfural selling price is very elastic and has fluctuated drastically over the past few years (Mordor Intelligence, 2021). Furthermore, the fixed operating costs, FCI, and glucose selling price have a lower impact on the profitability of the plant.

3.2.5 Plant Viability

Constructing an integrated process plant in Malaysia that uses EFB to manufacture glucose and furfural will result in a profitable process plant. According to market research, the demand for glucose and furfural is increasing rapidly in Malaysia (Persistence Market Research, 2020). Therefore, the process

plant can be upscaled in the future for a higher profit. Nonetheless, the plant's capacity is not projected to decline, implying that the plant will be profitable in the future. In addition, the selling price of furfural fluctuates greatly, currently showing a lower value in 2021 (Mordor Intelligence, 2021). As Malaysia is going through the phase of vaccination for the COVID-19 coronavirus, the economy of all the process plants is affected. After the vaccination phase, the country's economy is expected to recover, leading to a higher product selling price and higher NPV.

In terms of operating costs, the cellulase enzyme (catalyst) is the major cost driver of the process plant using EFB, which is cheap biomass available in Malaysia. As the research is conducted through simulation, the flow of catalyst and catalyst recycling is not considered, where installing an enzyme separation and recycling stream can reduce the variable cost greatly. In terms of FCI, the enzymatic reactor has the highest equipment cost because of its large residence time. Optimizing the reactor process condition can reduce the residence time resulting in a smaller reactor. Finally, various parameters can be further optimized in the process plant in the future, allowing for increased profit and sustainability.

4. Conclusion

In this work, an integrated process plant producing both glucose and furfural from EFB is designed and simulated using the most suitable process conditions to maximize the yield and purity of the product. The mass and energy balance results are obtained, and a PFD is drawn to support the equipment used in the plant. For a production capacity of 10 ktpy of glucose and 4.96 ktpy of furfural, purity of 98.21% and 99.54% is achieved, respectively. The plant economy is analyzed by obtaining the FCI, operating costs, and working capital, where the profitability is analyzed using CCF, NPV, and IRR. For the capacity of 10 ktpy of glucose and 4.96 ktpy of furfural, the FCI is calculated as MYR 81.61 million. The working and operating costs are calculated as MYR 11.29 million and MYR 46.92 million, respectively. On the evaluation of the profitability of the plant, the NPV, IRR, and ROI of the process plant are calculated as MYR 31.45 million, 14.25%, and 22.06%, respectively. From the obtained results, it can be concluded that the designed process plant is profitable, and this profit can be increased with optimization, which is suggested to be included in the future. Therefore, the designed integrated process plant reduces the waste from the palm oil mill, which makes it both a profitable and sustainable plant.

Abbreviations

No.	Symbols	Abbreviation
1	MSW	Municipal Solid Waste
2	MT	Metric Tons
3	EFB	Empty Fruit Bunch
4	MEBT	Mass and Energy Balance Table
5	GWP	Global Warming Potential
6	DE	Dextrose Equivalent
7	CARG	Compound Annual Growth Rate
8	ktpy	Kilotons per year
9	tpy	Tons per year
10	H_2O	Water
11	PFD	Process Flow Diagram
12	wt.%	Weight Percentage
13	ppm	Parts Per Million
14	°C	Degree Celsius
15	FCI	Fixed Capital Investment
16	NPV	Net Present Value
17	IRR	Internal Rate of Return
18	ROI	Return on Investment
19	VLE	Vapor Liquid Equilibrium
20	LLE	Liquid-Liquid Extraction
21	CPSPO1-1	Solid Molar Volume
22	VSPOLY-1	Solid Heat Capacity

Declarations

Data availability statement:

All data generated or analysed during this study are included in this published article (as an electronic supplementary file).

References

1. 21Food, 2021. Glucose syrup specification. (https://www.21food.com/products/glucose-syrup-2025807.html). (Accessed 12 March 2021).
2. Ajiwibowo, M.W., Darmawan, A., Aziz, M., 2019. Towards clean palm oil processing: Integrated ammonia production from empty fruit bunch and palm oil effluent. J. Cleaner Prod. 236, 117680.
3. Alaw, F.A., Sulaiman, N.S.a., 2019. A review of boiler operational risks in empty fruit bunch fired biopower plant. J. Chem. Eng. Ind. Biotechnol. 5(2), 29-35.
4. Aziz, M., Kurniawan, T., Oda, T., Kashiwagi, T., 2017. Advanced power generation using biomass wastes from palm oil mills. Appl. Thermal Eng. 114, 1378-1386.
5. Basso, A., Serban, S., 2020. Overview of immobilized enzymes' applications in pharmaceutical, chemical, and food industry, Immobilization of Enzymes and Cells. Springer, pp. 27-63.
6. Chiesa, S., Gnansounou, E., 2014. Use of empty fruit bunches from the oil palm for bioethanol production: a thorough comparison between dilute acid and dilute alkali pretreatment. Bioresour. Technol. 159, 355-364.
7. Contreras-Zarazúa, G., Martin-Martin, M., Sánchez-Ramirez, E., Segovia-Hernández, J.G., 2022. Furfural production from agricultural residues using different intensified separation and pretreatment alternatives. Economic and environmental assessment. Chem. Eng. Process. 171, 108569.
8. Dolphin Centrifuge, 2021. Decanter centrifuge. (https://dolphincentrifuge.com/difference-between-decanter-centrifuge-disc-centrifuge/). (Accessed 6 April 2021).
9. Ebert, J., 2008. Furfural: future feedstock for fuels and chemicals, Biomass Magazine
10. Ellis, C., 2018. World Bank: global waste generation could increase 70% by 2050. (https://www.wastedive.com/news/world-bank-global-waste-generation-2050/533031/). (Accessed 2 March 2021).
11. Geng, A., 2013. Conversion of oil palm empty fruit bunch to biofuels. Liquid, Gaseous and Solid Biofuels-Conversion Techniques, InTech, Croatia, 479-490.
12. Hafyan, R.H., Bhullar, L.K., Mahadzir, S., Bilad, M.R., Nordin, N.A.H., Wirzal, M.D.H., Putra, Z.A., Rangaiah, G.P., Abdullah, B., 2020. Integrated biorefinery of empty fruit bunch from palm oil industries to produce valuable biochemicals. Processes 8(7), 868.
13. Hongye Holding Group Corporation Ltd., 2020. Furfural specification. (https://www.go4worldbusiness.com/product/view/1143815/furfural.html). (Accessed 15 March 2021).
14. Hossain, M.S., Theodoropoulos, C., Yousuf, A., 2019. Techno-economic evaluation of heat integrated second generation bioethanol and furfural co-production. Biochem. Eng. J. 144, 89-103.
15. Humbird, D., Davis, R., Tao, L., Kinchin, C., Hsu, D., Aden, A., Schoen, P., Lukas, J., Olthof, B., Worley, M., 2011. Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol: dilute-acid pretreatment and enzymatic hydrolysis of corn stover. National Renewable Energy Lab.(NREL), Golden, CO (United States).

16. IHS Markit, 2020. Furfural -chemical economics handbook. (https://ihsmarkit.com/products/furfural-chemical-economics-handbook.html). (Accessed 15 March 2021).
17. Kenthorai Raman, J., Gnansounou, E., 2015. Furfural production from empty fruit bunch – A biorefinery approach. Ind. Crops Prod. 69, 371-377.
18. LHDN Malaysia, 2020. Corporate tax rate in 2020. (http://www.hasil.gov.my/bt_goindex.php?bt_kump=5&bt_skum=2&bt_posi=5&bt_unit=1&bt_sequ=1). (Accessed 30 April 2021).
19. Liquiflo, 2016. Liquiflo chemical processing pump. (http://www.liquiflo.com/v2/files/pdf/applicationnotes/AN1602-4-MinFlowRateforCentrifugalPumps-Feb2016.pdf). (Accessed 5 April 2021).
20. Loh, S.K., 2018. Optimisation of process conditions for ethanol production from enzymatically saccharified empty fruit bunch using response surface methodology (RSM). J. Oil Palm Res. 30.
21. Malaysia Indeed, 2021. Average base salary in Malaysia 2021. (https://malaysia.indeed.com/career/factory-worker/salaries). (Accessed 30 April 2021).
22. Manual, A.P., 2001. Physical property systems, physical property methods and models 11.1. Aspen Technology Inc.
23. Mittal, A., Black, S.K., Vinzant, T.B., O'Brien, M., Tucker, M.P., Johnson, D.K., 2017. Production of furfural from process-relevant biomass-derived pentoses in a biphasic reaction system. ACS Sustain. Chem. Eng. 5(7), 5694-5701.
24. Mordor Intelligence, 2021. Furfural market – growth, trends, covid-19 impact, and forecast (2021-2026). (https://www.mordorintelligence.com/industry-reports/furfural-market). (Accessed 13 March 2021).
25. MPCO, 2021. Malaysian Palm Oil Industry. (http://mpoc.org.my/malaysian-palm-oil-industry/). (Accessed 4 March 2021).
26. Nhien, L.C., Long, N.V.D., Kim, S., Lee, M., 2017. Techno-economic assessment of hybrid extraction and distillation processes for furfural production from lignocellulosic biomass. Biotechnol. 10, 81-81.
27. Nhien, L.C., Long, N.V.D., Lee, M., 2021. Novel hybrid reactive distillation with extraction and distillation processes for furfural production from an actual xylose solution. Energies 14(4), 1152.
28. Ninduangdee, P., Kuprianov, V.I., 2016. A study on combustion of oil palm empty fruit bunch in a fluidized bed using alternative bed materials: Performance, emissions, and time-domain changes in the bed condition. ApEn 176, 34-48.
29. Persistence Market Research, 2020. Glucose and fructose market. (https://www.persistencemarketresearch.com/market-research/glucose-and-fructose-market.asp). (Accessed 12 March 2021).
30. Peters, M.S., Timmerhaus, K.D., West, R.E., 2003. Plant design and economics for chemical engineers. McGraw-Hill New York.
31. Piarpuzán, D., Quintero, J.A., Cardona, C.A., 2011. Empty fruit bunches from oil palm as a potential raw material for fuel ethanol production. Biomass Bioenergy 35(3), 1130-1137.

32. Sarungalo, Z., 2005. Production and characterization of glucose syrup of papuan sago starch, Sago Palm Development and Utilization. Proceeding of the Eight International Sago Symposium (8ISS), Universitas Negeri Papua, Indonesia.
33. Sinnott, R., Towler, G., 2020. Chapter 6 - Costing and project evaluation, in: Sinnott, R., Towler, G. (Eds.), Chemical Engineering Design (Sixth Edition). Butterworth-Heinemann, pp. 275-369.
34. The World Bank, 2021. Trends in solid waste management. (https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html). (Accessed 30 December 2021).
35. UN Data, 2018. Glucose and furfural Data. (http://data.un.org/). (Accessed 12 March 2021).
36. Vargas-Mira, A., Zuluaga-García, C., González-Delgado, A.D., 2019. A Technical and Environmental Evaluation of Six Routes for Industrial Hydrogen Production from Empty Palm Fruit Bunches. ACS Omega 4(13) 15457-15470.
37. Wilson, R., Lilly, M., 1969. Preparation and use of insolubilized amyloglucosidase for the production of sweet glucose liquors. Biotechnol. Bioeng. 11(3), 349-362.
38. Wooley, R.J., Putsche, V., 1996. Development of an ASPEN PLUS physical property database for biofuels components. United States.
39. XE currency, 2021. Conversion rate of USD to MYR in May 2021. (https://www.xe.com/currencyconverter/convert/?Amount=1&From=USD&To=MYR). (Accessed 30 April 2021).
40. Zafar, S., 2021. Everything you need to know about biomass energy system. (https://www.bioenergyconsult.com/tag/biomass-wastes/). (Accessed 5 March 2021).

Figures

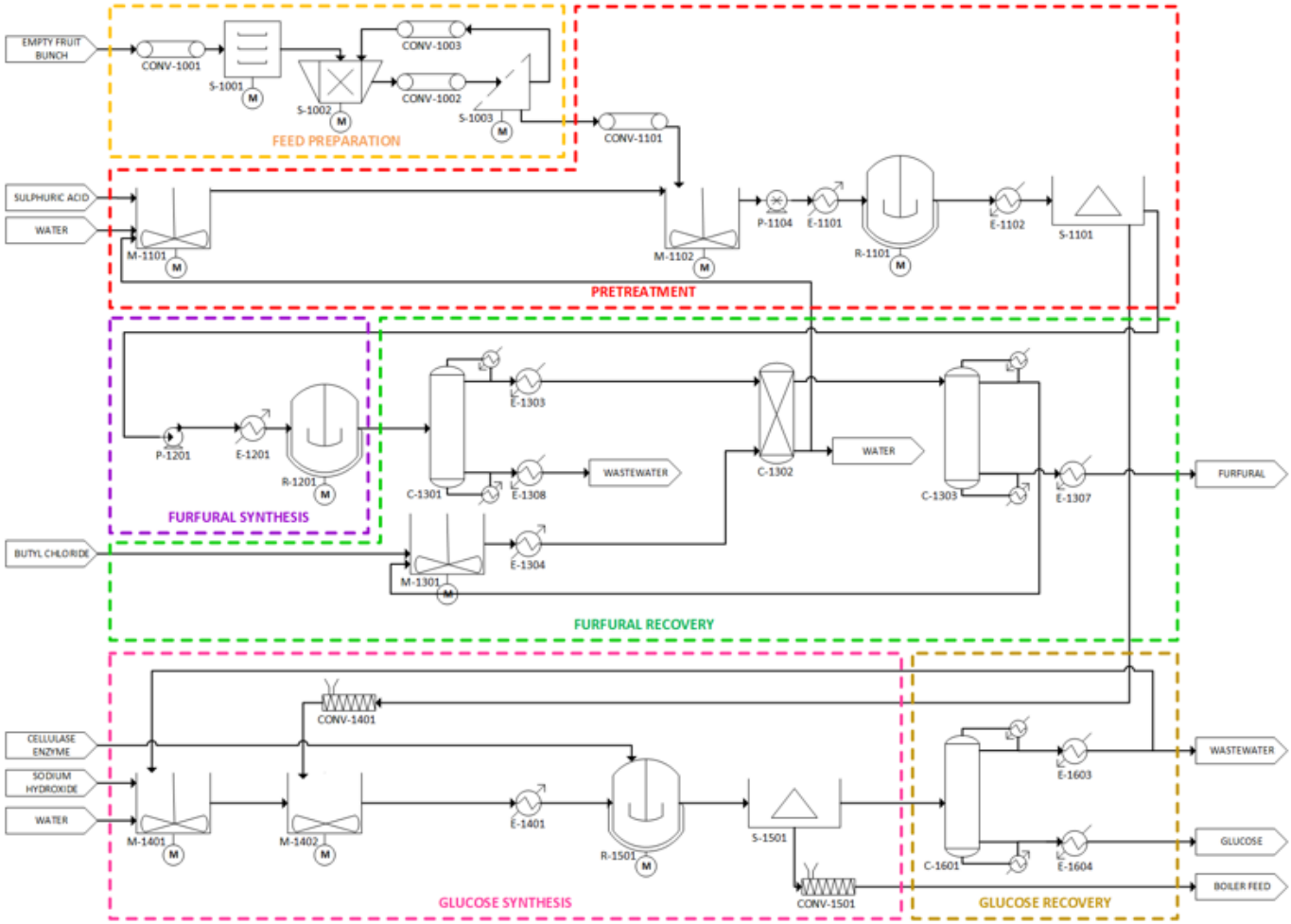


Figure 1

Integrated production of glucose and furfural from empty fruit bunch

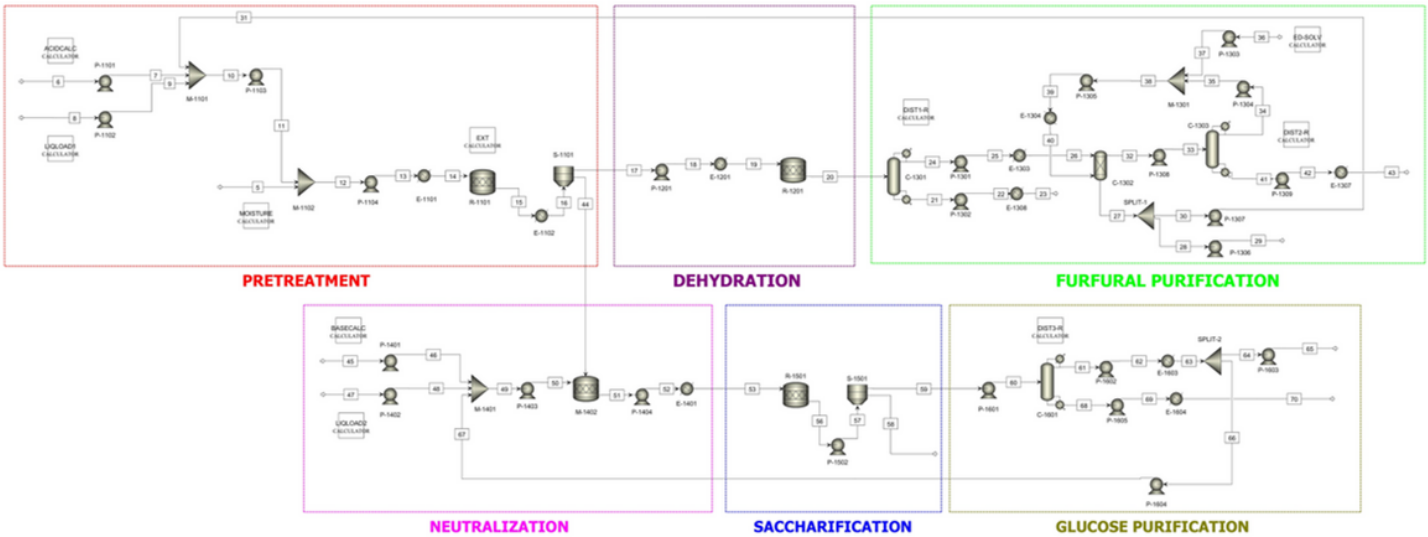


Figure 2

Simulation flow diagram of the integrated process.

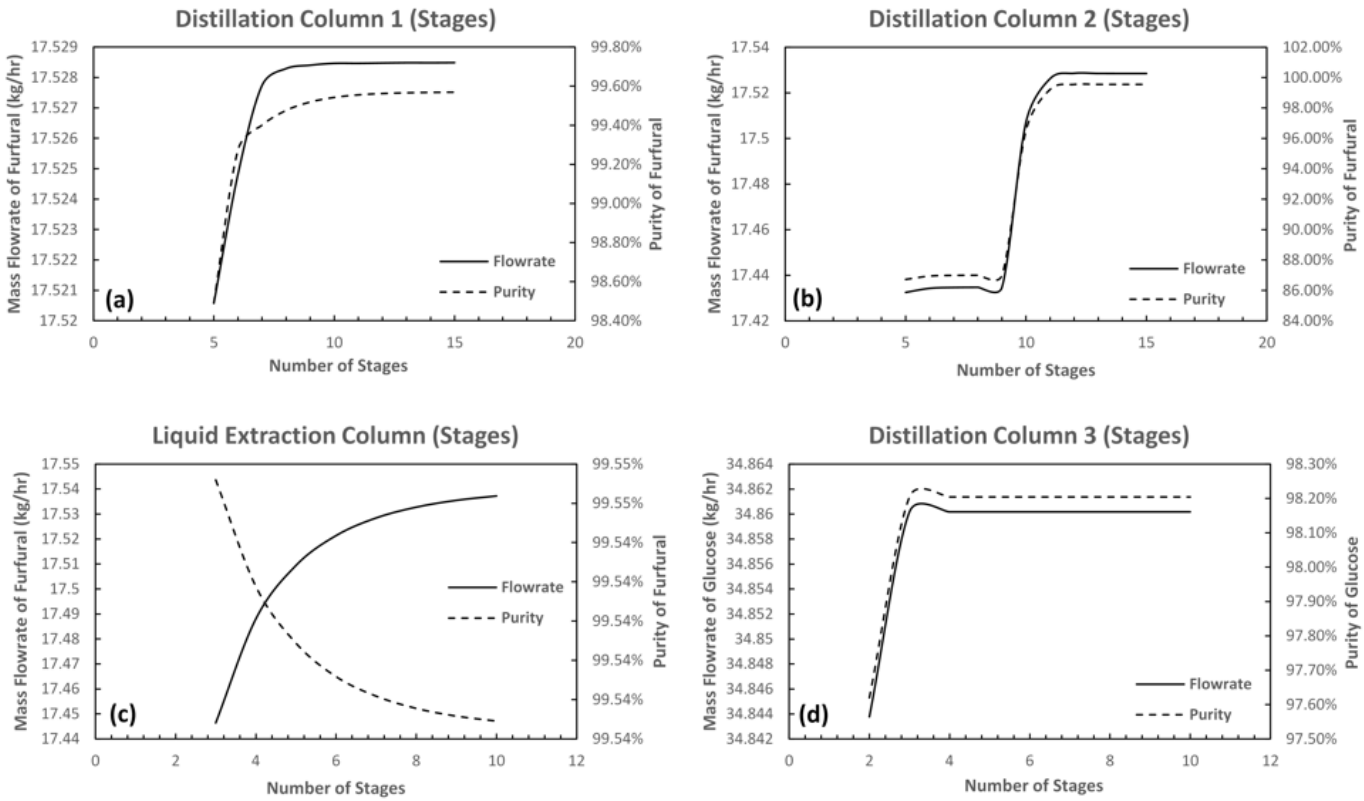


Figure 3

Variation of number of stages of (a) distillation column 1, (b) distillation column 2, (c) distillation column 3, and (d) liquid-liquid extraction column

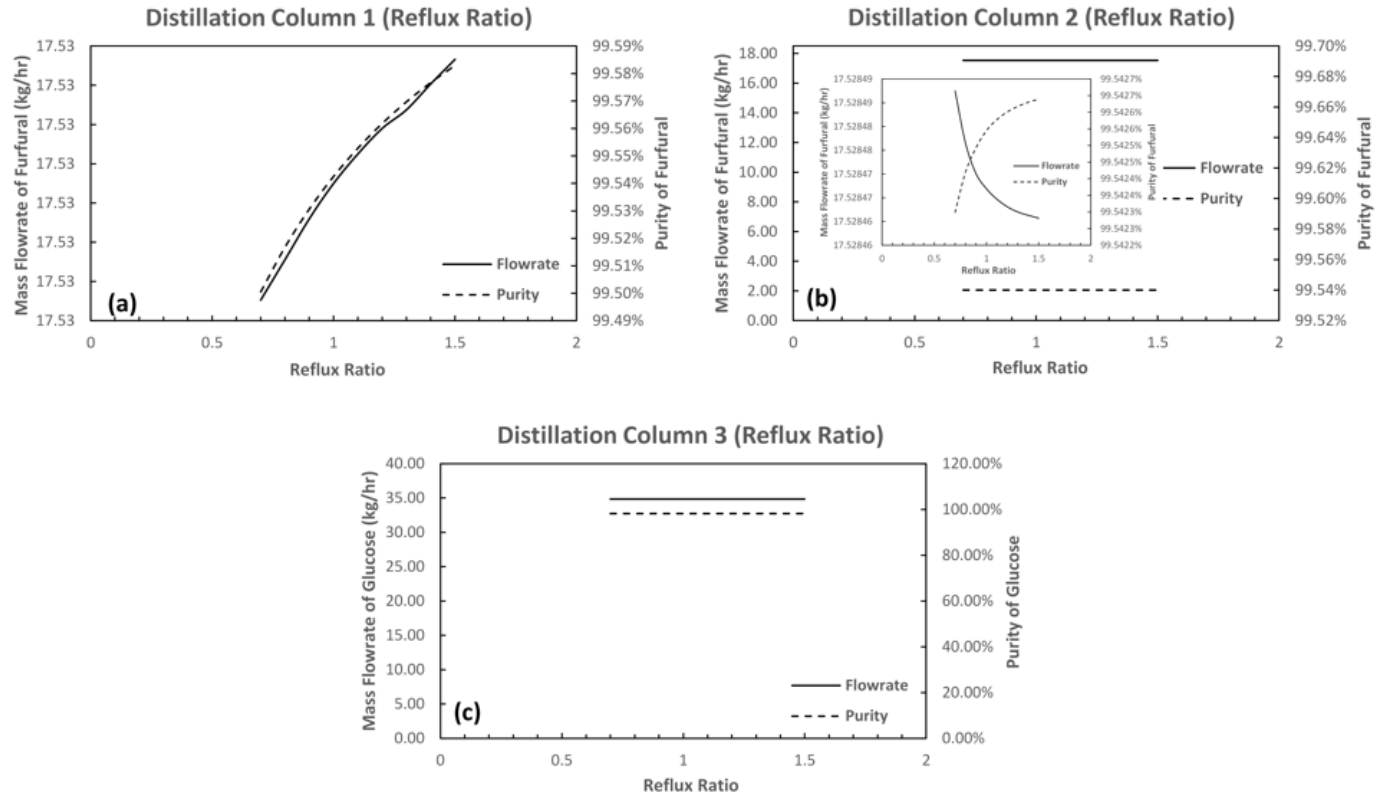


Figure 4

Variation of reflux ratio of (a) distillation column 1, (b) distillation column 2 and (c) distillation column 3.

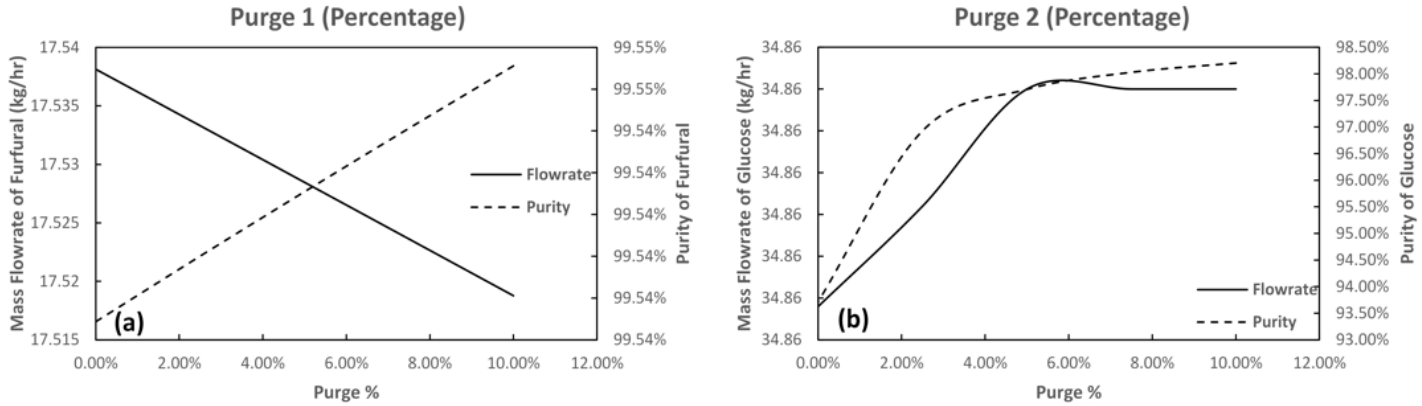


Figure 5

Variation of purge percentage of (a) recycle 1 and (b) recycle 2.

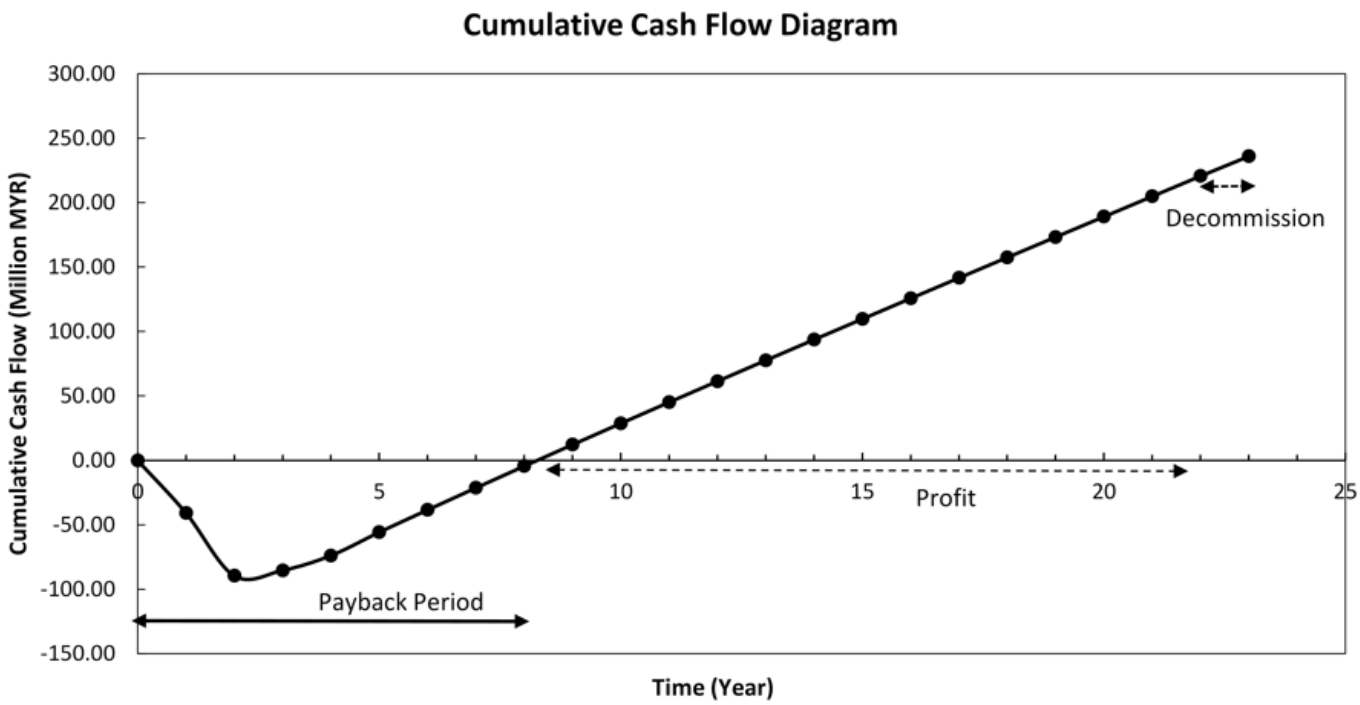


Figure 6

Cumulative cash flow diagram (CFF).

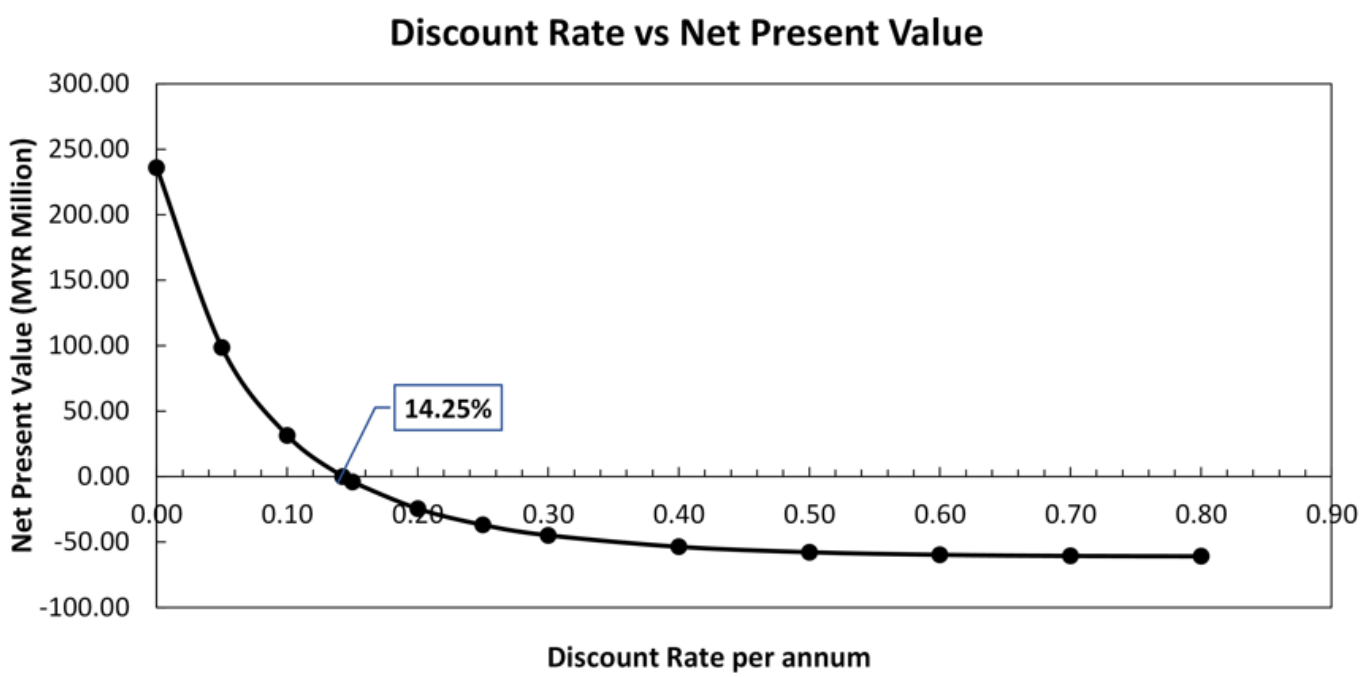
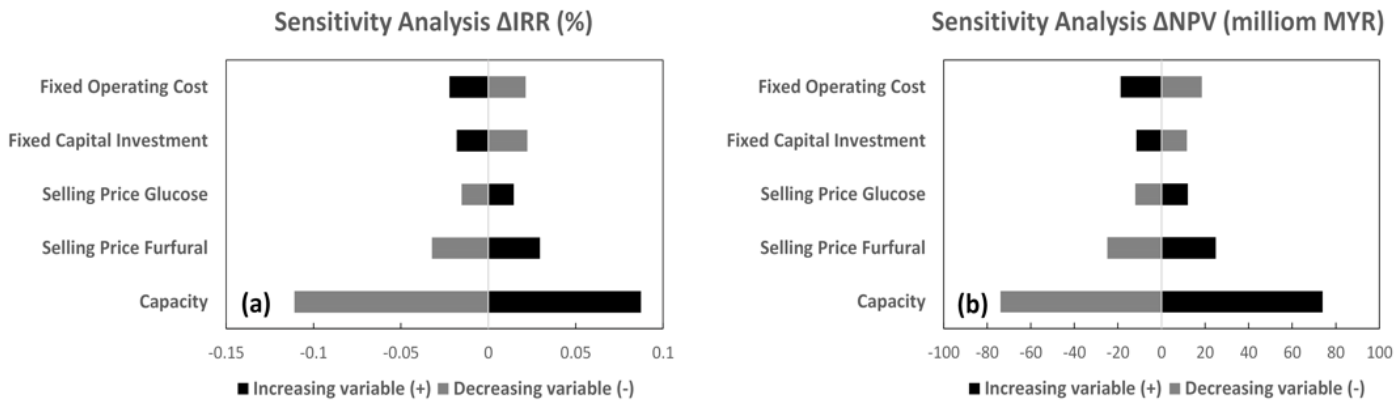


Figure 7

Net present value against discount rate per annum.



(c)

Parameter	Variation (%)
Total Capacity	± 20
Selling Price Furfural	± 10
Selling Price Glucose	± 10
Fixed Capital Investment	± 15
Fixed Operating Cost	± 10

Figure 8

(a) change in NPV with various parameter changes; (b) change in IRR with various parameter changes; (c) Parameter change for sensitivity analysis

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- GraphicalabstractglucosefurfuralSZZW19Jan.docx
- AppendixZafranAPZW19Jan.docx