

Bioethanol Production from Palm Biomass Residues and Techno-Economic Analysis Using Superpro Designer Software

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ABSTRACT

This study investigates ethanol production from palm biomass residues using SuperPro Designer software. Palm biomass, which resembles bamboo in structural properties, is largely underutilized despite being abundant in major palm oil-producing countries like Indonesia and Malaysia. Approximately 90% of palm biomass is wasted post-harvest. With cellulose, hemicellulose, and lignin contents of 38.7%, 23.8%, and 19.4% respectively (dry weight basis), palm biomass presents a valuable feedstock for bioethanol. A process model was developed to produce 88 million gallons of ethanol annually from 1000 MT/day of feedstock. The estimated annual operating cost is \$222 million, with a net unit production cost of \$0.66/kg. Economic indicators such as return on investment and payback time were calculated using selling prices of \$0.90/kg for ethanol and \$1.24/kg for ionic liquid. Ionic liquids, used during pretreatment, are recovered at rates of 95-98%. Lignin, produced at 630 MT/day, is not included in revenue projections but could significantly improve profitability if marketed.

Keywords: Palm Biomass, Techno-Economic Analysis, Ethanol, Cost Analysis, SuperPro Designer.

INTRODUCTION

Bioethanol is a suitable resource for renewable energy derived from lignocellulosic biomass, apart from being used as energy source ethanol can be used for manufacturing several other industrial products as well such as cosmetics, pharmaceuticals, and polymer products. Due to the limited reserve of fossil fuels, bioethanol can replace them and reduce the carbon dioxide emissions. Cellulose, hemicellulose are the components which are used for ethanol production following pretreatment, thermal and enzymatic hydrolysis, and fermentation. The nature of biomass and its cellulose and hemicellulose contents are the main factors for higher yield of ethanol and can differ based on the source of biomass and available technological aspects. The improvement on pretreatment, hydrolysis and fermentation based on operating conditions are the key components to produce ethanol on industrial scale (Hashmi et al., 2017a; Jung et al., 2011; Maulidin et al., 2023; Zabed et al., 2016).

In recent years, the scope of research on ethanol production has extended based on different types of biomasses and their availability, cellulose content, product yields, diversity on using in various commercial applications. Based on accessibility and low-cost, palm plant trunks and branches can be considered as promising feedstock for ethanol production. The main interest in palm biomass as potential ethanol resource due to abundance in the south China regions including Indonesia, Malaysia, Thailand, Philippines, and this biomass mainly wasted after harvesting palm fruits and remain in the fields for natural decomposition as for soil fertilization. Among these, Indonesia (52.3%) and Malaysia (33.1%) are the world's largest palm oil producers, followed by Thailand (3.1%) which leads to huge amount of palm biomass residue. The environmental aspects, efficient pretreatment methods, greater extent of reaction during hydrolysis and fermentation can support palm biomass as renewable energy resource for ethanol production (Ilyas et al., 2022; Jung et al., 2011; Maulidin et al., 2023).

The aim of this report is to represent palm biomass as potential feedstock of ethanol production through available methods. In addition, the feedstock description, cultivation and harvesting in south China regions and cost involved for ethanol production also discussed. Several strategies have been reviewed for this purpose, including pretreatment methods, composition analysis, product processing methods, yield, Techno-economic analysis (TEA). Consequently, the industrial applications, profitability, and feasible methods of palm biomass based biorefinery will be studied as well. The SuperPro designer software is used to develop process flow diagram and optimization for ethanol production from palm biomass, and product processing, possible yields, operating conditions are also assumed and designed.

Palm Biomass Feedstock

Feedstock description

The palm trunks and branches can be collected after harvesting the palm oil fruits, and according to the report 15.2 million tons of oil palm trunks are generated annually in Malaysia only. Generally, the cortex is just below the bark of the trunk, thus making up the outer layer of the stem. The peripheral region consisting of parenchymal layers and vascular bundles contributed the most to the mechanical support for the oil palm. The palm biomass collection and harvesting process shown in figure 1. From the figure 1, it can be seen that after palm oil fruits harvesting from the palm trees, and proceeded for oil and other product processing purposes, and then the branches and trunks are cutting down into smaller pieces and left on the side to the cultivated fields. The air-dried palm biomass kindly donated to the Tropical Chase (Malaysia) for crushing to 18-120 mesh size. The ethanol production from these wasted palm biomasses can be the effective and productive way of disposal (Ilyas et al., 2022; Jung et al., 2011; Maulidin et al., 2023).

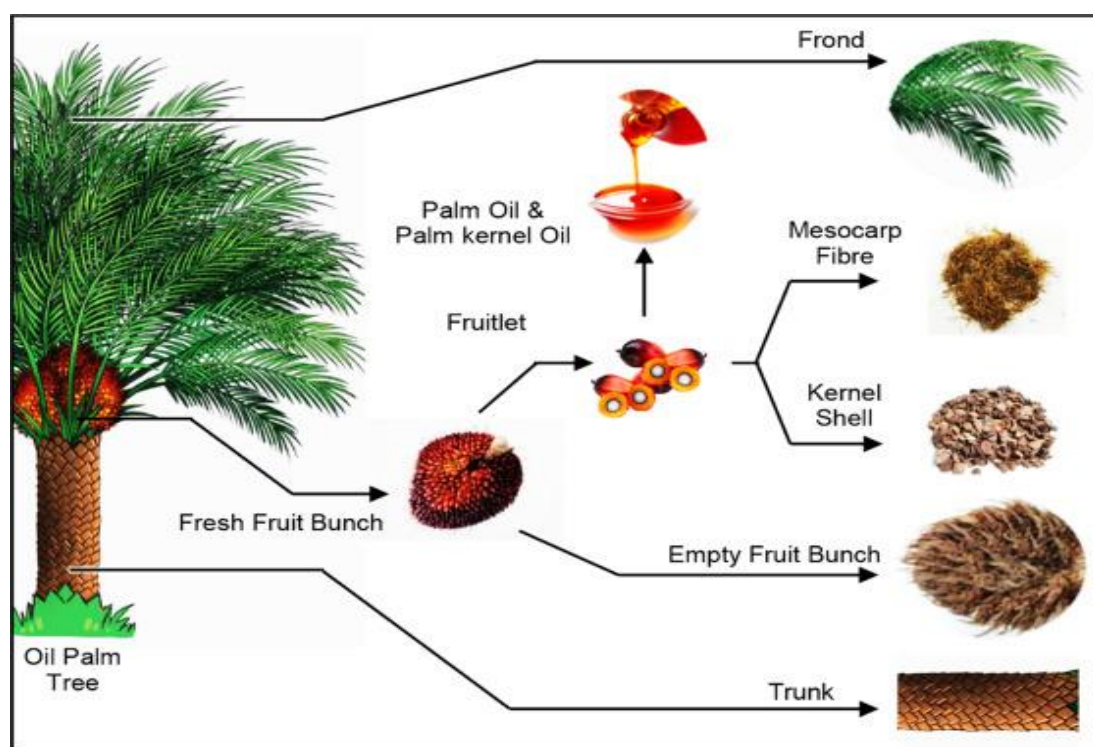


Figure 1: Palm lignocellulosic fiber biomass (Ilyas et al., 2022).

Feedstock Composition Analysis

The main components of palm biomass are cellulose, hemicellulose, and lignin. Ethanol can be produced from cellulose and hemicellulose, and lignin can be separated as co-product and lignin is not used for conversion to ethanol. The amount of cellulose, hemicellulose and lignin are shown in Table 1. The ground oil palm trunks and branches contained 38.7%, 14.7%, 9.1%, 6.4%, 2.3%, 19.4% and 5.4% (w/w) of glucan, Xylan, arabinan, mannan, Galactan, acid-insoluble lignin and ash, respectively, on a dry weight basis. Other remaining constituents are extractives, including minerals, proteins, sugar, starch, tanning agents, fats, and resins.

Table 1: Palm biomass composition (Dry basis) (Ilyas et al., 2022; Jung et al., 2011).

Component	% w/w
Cellulose	38.7
Hemicellulose	23.8
Lignin	19.4
Other Solids	12.7
Ash	5.4

Ionic Liquid for Palm Biomass Pretreatment

A variety of pretreatment techniques have been used for lignocellulosic biomass conversion into biofuels based on product yields. The ionic liquid (IL) pretreatment has drawn the most attention recently, due to it has unique physical and chemical properties, and a very stable organic salts to be considered as green solvent. IL (1-butyl-3-methylimidazolium) method is very effective pretreatment method, and it weakens the van der Waals interactions between cell wall components. The suggested IL and biomass ratio is 1:20 (5% w/w to biomass), and IL boiling point is less than 100 °C and can easily recovered by distillation (Hashmi et al., 2017a; Usmani et al., 2020). The general functions and properties of IL are given below:

- Ionic Liquids (IL) are green alternatives to volatile organic solvents, as no hazardous chemicals are formed by their application.
- ~100% recovery of the IL used is possible.
- ILs are entirely organic in nature constituting both anionic and cationic species.
- Non-flammability, very low vapor pressure, high viscosity, low conductivity, and high thermal and chemical stability.
- ILs are non-corrosive, economical, have good biodegradability and non-toxic.
- ILs have strong hydrogen bonding coordination making them unique in their ability to dissolve the complete biomass rather than individual subcomponents and refers to higher extent of reactions.

Process Description

Based on the available information and reactions conditions and yield of ethanol production from palm biomass, a process flow diagram, block diagram and table about process descriptions are developed based on SuperPro designer software. The block diagram of ethanol production from palm biomass is presented in figure 2. All the reactions and reaction conditions, yields, catalyst loading, and extent of reaction are presented in table 2 and table 3.

From the figure 3 and table 2, it can be depicted that the after harvesting palm oil fruits then palm trunks and branches are shredded (P-2/SR-101) for 4-5 mesh size and then washed (P-6/WSH-101) by water, then mixed (P-3/MX-102) with pure water and ionic liquid and proceeded for thermal hydrolysis (P-7/R-101) where the cellulose and hemicellulose will hydrolysed by the temperature at 180 °C for 2 h; then water and ionic liquid are separated by flash (P-9/V-101) vapour phase separation; after cooling the enzymatic hydrolysis (P-12/R-102) step have completed by supplying enzyme at 50°C for 72 h; then the produced glucose and xylose sent for fermentation (P-14/FR-101) at 35°C for 72 h with yeast to produce ethanol; and ethanol and lignin are separated by the distillation process (P-16/C-101) and (P-17/C-102); simultaneous ionic liquid recovery conducted by using another two distillation column (P-4/C-103) and (P-21/C-104) and finally around 95-98% ionic liquid can be recovered.

The table 3 represents that 3% (assumed) of the available glucose and xylose goes for Yeast formation and 96% and 80% to ethanol production, and all other reaction happened in the thermal and enzymatic hydrolysis reactors. The process flow diagram has been designed and developed by using SuperPro designer software for 1000MT/day ethanol production from palm biomass and presented in figure 3. Figure 3 represents the process modelling, required equipment's, and their design and connection for ethanol production from palm biomass.

The required raw materials, enzyme and yeast loading have been presented in table 3. The amount of lignin produced as co-product after ethanol production is 630 MT/day and ethanol production yield 30.9%.

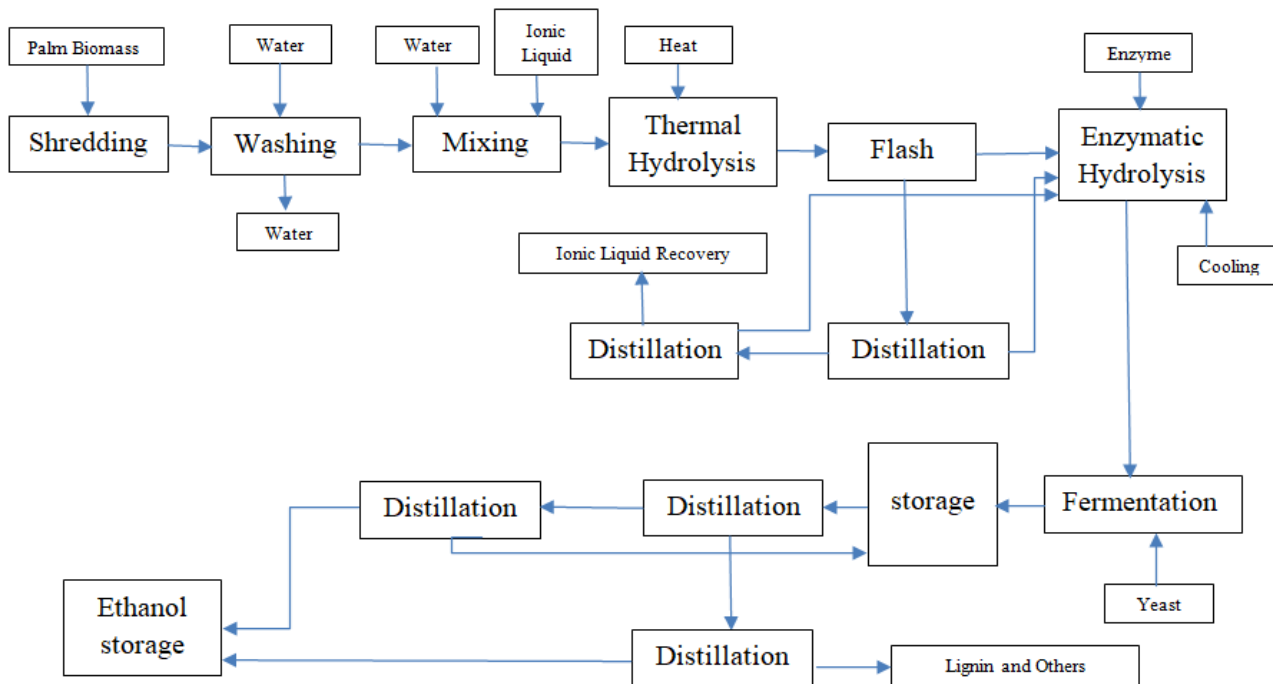


Figure 2: Block diagram for ethanol production from palm biomass

Table 2: Block description of process simulation using superpro designer software.

Production capacity: 1000 MT/Day ethanol, Operation Day: 330, 24 h		
Total Biomass: 3250 MT/Day, Lang Factor 4		
Name of Operation	Description	Ref.
Shredding	4-5 mash size	(Hashmi et al., 2017b)
Washing	Cleaning of biomass	(Zabed et al., 2016)
Mixing-I	Mixing of water and Ionic Liquid (5% of biomass)	(Maulidin et al., 2023; Zabed et al., 2016)
Mixing-II	Mixing of water, Ionic Liquid and Biomass	(Maulidin et al., 2023; Zabed et al., 2016)
Heat Exchanging-I	Hot Fluids: water and Ionic Liquid from flash distillation	(Hashmi et al., 2017a; Kumar and Murthy, 2011)
Thermal Hydrolysis	180 °C, 2h, Extent of Reaction: Cellulose 70%, Xylose 80%	(Kumar and Murthy, 2011; Zabed et al., 2016)
Flash	Adiabatic, 84% Ionic liquid, 90% water separated by phase separation	(Kumar and Murthy, 2011; Natelson et al., 2015; Pardo-Planas et al., 2017)
Cooling-I	Exit temperature 50 °C,	(Hashmi et al., 2017a; Kumar and Murthy, 2011)
Enzymatic Hydrolysis	50°C, 72 h, Extent of Reaction: Cellulose 97.4%, Xylose 98.6%, Enzyme loading 3% of cellulose and Hemicellulose	(Bbosa et al., 2018; Hashmi et al., 2017a; Kumar and Murthy, 2011; Zabed et al., 2016)
Storage-I	Intermediate storage Glucose, Xylose, Cellulose, Hemicellulose, lignin and others, 1 h	(Kumar and Murthy, 2011; Zabed et al., 2016)
Fermentation	35°C, 72 h, Extent of Reaction: Glucose 96%, Xylose 80%, Yeast 3% of Glucose and Xylose	(Kumar and Murthy, 2011; Zabed et al., 2016)
Storage-II	Intermediate storage Yeast (<i>Saccharomyces cerevisiae</i>), 1 h	(Kumar and Murthy, 2011; Zabed et al., 2016)
Storage-III	Intermediate storage produced Ethanol and others, 1 h	(Kumar and Murthy, 2011; Zabed et al., 2016)

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Table 3: Reactions involved in the reactors for ethanol production from palm biomass (Amornraksa et al., 2020; Zabed et al., 2016).

Thermal Hydrolysis				Extent of Reaction
Cellulose	+	Water	====>	Glucose
162 g		18 g		180 g
Hemicellulose	+	Water	====>	Xylose
132 g		18 g		150 g
Enzymatic Hydrolysis				
Cellulose	+	Water	====>	Glucose
162 g		18 g		180 g
Hemicellulose	+	Water	====>	Xylose
132 g		18 g		150 g
Fermentation				
Glucose	====>	Yeast	+	CO ₂ + Water
100 g		60 g		20 g 20 g
Glucose	====>	EtOH	+	CO ₂
180 g		88 g		92 g
Xylose	====>	Yeast	+	CO ₂ + Water
100 g		60 g		20 g 20 g
Xylose	====>	EtOH	+	CO ₂
150 g		76 g		74 g

Cost Analysis

The developed design to produce ethanol from palm biomass, which is an abundant source of lignocellulosic biomass in the south China regions. The plant scale for the 1000 MT/day ethanol production and the base case has a feedstock flowrate of 3250 MT/day of wet biomass of palm biomass for 330 operation days, 24 working hours per day, and lang factor 4. The annual executive summary of the designed process is presented in the table 4. The table 4 is copied from Economic Evaluation Report (ERR) generated by SuperPro designer. From the table 4 the information can be depicted that the production cost of ethanol from palm biomass is optimum due to the low raw material cost. The cost is calculated as reference year of 2010 (Bbosa et al., 2018; Humbird et al., 2011; Kumar and Murthy, 2011). The table 4 displays the key economic information's for the target ethanol production and the total capital investment is roughly \$529 million. The estimated annual operating cost \$ 222 million, which results in a unit production and net unit production cost \$ 0.66/kg. the results calculated for the return on investment, payback time etc. based on selling price \$ 0.9/kg ethanol, and \$ 1.24/kg ionic liquid. The produced lignin 630 MT/day not added to the revenue, if lignin selling price added as revenue, then the total revenue will be much higher, and the payback time will be less.

Table 4: Executive summary (2010 Prices)

Total Capital Investment	528,905,000 \$
Capital Investment Charged to This Project	528,905,000 \$
Operating Cost	222,316,000 \$/yr
Main Revenue	300,971,000 \$/yr
Other Revenues	55,657,973 \$/yr
Total Revenues	356,629,000 \$/yr
Cost Basis Annual Rate	334,412,150 kg MP/yr
Unit Production Cost	0.66 \$/kg MP
Net Unit Production Cost	0.66 \$/kg MP
Unit Production Revenue	1.07 \$/kg MP
Gross Margin	37.66 %
Return On Investment	24.09 %
Payback Time	4.15 years
IRR (After Taxes)	17.58 %
NPV (at 7.0% Interest)	383,826,000 \$
MP = Total Flow of Stream 'Ethanol'	

Table 5 and figure 4 represents the annual operating cost for all cost items and pie chart for operating cost breakdown, and showing which can contribute the maximum costs. From the figure 4, its can be seen that the facility dependent cost is the greatest contributor (42%) to the annual operating costs, followed by the raw materials (38%) and utilities costs (12%). The facility dependent cost is calculated based on the equipment's usage and availability rates, lumped facility rates, production rate of the process, depreciation, maintenance, and miscellaneous factory expenses. The economic results in the figure 7 are calculated based upon the literatures and NREL report (Bbosa et al., 2018; Humbird et al., 2011; Kumar and Murthy, 2011).

Table 5: Annual operating cost (2010 Prices)

Cost Item	\$	%
Raw Materials	83,843,000	37.71
Labor-Dependent	15,682,000	7.05
Facility-Dependent	94,130,000	42.34
Laboratory/QC/QA	2,352,000	1.06
Consumables	0	0.00
Waste Treatment/Disposal	0	0.00
Utilities	26,309,000	11.83
Transportation	0	0.00
Miscellaneous	0	0.00
Advertising/Selling	0	0.00
Running Royalties	0	0.00
Failed Product Disposal	0	0.00
TOTAL	222,316,000	100.00

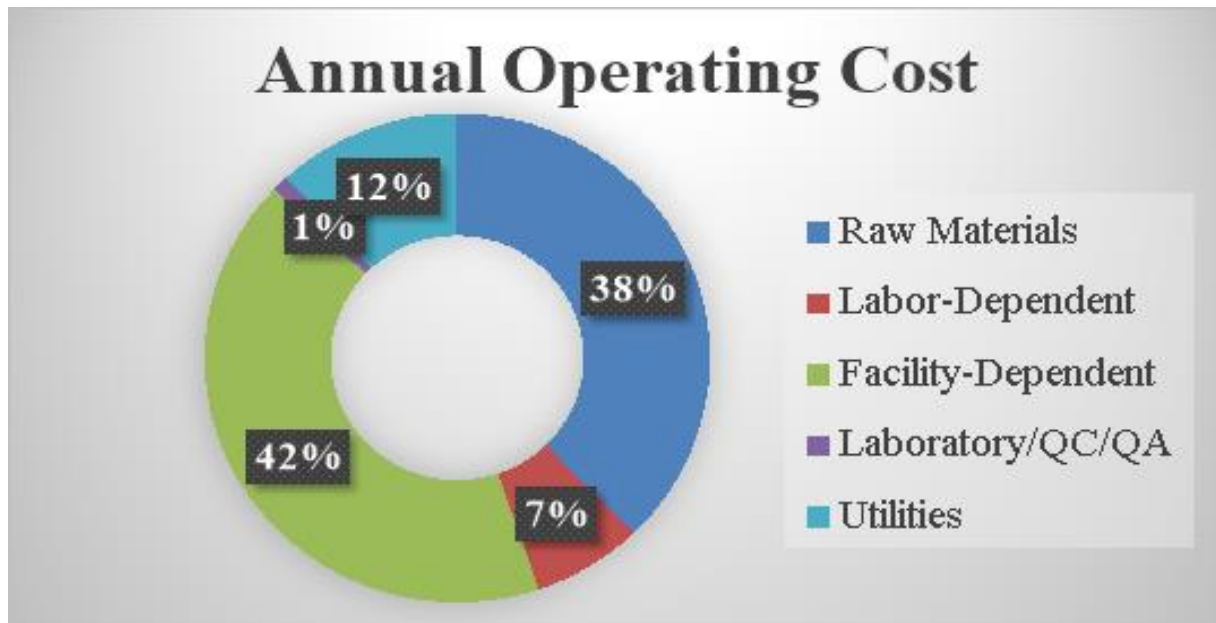


Figure 4: Annual operating costs (Pie Chart)

The table 6 displays the breakdown of the materials cost. The cost of enzymes is estimated by specifying a purchasing price that corresponds to \$0.4/gal of ethanol produced. The industry's objective is to drive that cost down to \$0.1/gal of ethanol through R&D in the future. The biomass cost is minimum due to the availability and only the main cost is involved due to the transportation. The ionic liquid price is \$ 1.24/kg, but the total ionic liquid cost can be recovered as revenue after the ionic liquid recovery process. The table 7, which is copied from the economic analysis, provides detailed information on utilities costs. The unit cost of steam (representing low pressure steam) is set to zero because it is produced on-site in the Utilities section. The maximum cost involved for power (36.41%) followed by the steam (25.28%) then high-pressure steam (15%), colling water (12.63%), and chilled water (10.7%).

Table 6: Raw materials cost (2010 Prices)

Bulk Material	Unit Cost (\$)	Annual Amount		Annual Cost (\$)	%
Biomass	0.00	1,072,500,000	kg	1,072,500	1.28
Enzymes	0.04	1,584,000	kg	63,360	0.08
Ionic liquid	1.24	54,450,000	kg	67,518,000	80.53
Water	0.00	86,592,000	kg	8,659	0.01
Yeast	2.30	6,600,000	kg	15,180,000	18.11
TOTAL				83,842,519	100.00

NOTE: Bulk material consumption amount includes material used as:

- Raw Material
- Cleaning Agent
- Heat Transfer Agent (if utilities are included in the operating cost)

Table 7: Utilities cost (2010 prices)

Utility	Unit Cost (\$)	Annual Amount	Ref. Units	Annual Cost (\$)	%
Std Power	0.10	95,785,666	kW-h	9,578,567	36.41
Steam	12.00	554,147	MT	6,649,764	25.28
Steam (High P)	20.00	197,163	MT	3,943,259	14.99
Cooling Water	0.05	66,475,339	MT	3,323,767	12.63
Chilled Water	0.40	7,034,640	MT	2,813,856	10.70
TOTAL				26,309,212	100.00

The Profitability Analysis is shown in table 8, which is copied from the project economic evaluation report. The revenue is generated by the ethanol production and recovered ionic liquid but the produced lignin as co-product not added as revenue, if lignin selling price is added then the plant will be profitable, and the payback will be reduced as well. The product (ethanol) unit selling price is \$0.9/kg whereas the production cost is \$0.66/kg (this includes all governmental subsidies), and the recovered ionic liquid selling price is \$1.24/kg. The designed plant can generate 88 million gallons fuel-grade ethanol per year, and the selling price (Produced ethanol) is \$ 3.4/gallon. The gross margin is 37.66%, return on investment 24.09%, and payback time 4.15 years.

Table 8: Profitability analysis for ethanol production from palm biomass.

Direct Fixed Capital	492,824,000 \$
Working Capital	11,439,000 \$
Startup Cost	24,641,000 \$
Up-Front R&D	0 \$
Up-Front Royalties	0 \$
Total Investment (A+B+C+D+E)	528,905,000 \$
Investment Charged to This Project	528,905,000 \$
Revenue/Savings Rates	
Ethanol (Main Revenue)	334,412,150 kg /yr
Ionic Liquid Recovery (Revenue)	44,885,482 kg /yr
Revenue/Savings Price	
Ethanol (Main Revenue)	0.90 \$/kg
Ionic Liquid Recovery (Revenue)	1.24 \$/kg
Revenues/Savings	
Ethanol (Main Revenue)	300,970,935 \$/yr
Ionic Liquid Recovery (Revenue)	55,857,973 \$/yr
Total Revenues	356,828,908 \$/yr
Total Savings	0 \$/yr
Annual Operating Cost (AOC)	
Actual AOC	222,316,000 \$/yr
Net AOC (K1-J2)	222,316,000 \$/yr
Unit Production Cost /Revenue	
Unit Production Cost	0.66 \$/kg MP
Net Unit Production Cost	0.66 \$/kg MP
Unit Production Revenue	1.07 \$/kg MP
Gross Profit (J-K)	134,313,000 \$/yr
Taxes (40%)	53,725,000 \$/yr
Net Profit (M-N + Depreciation)	127,406,000 \$/yr
Gross Margin	37.66 %
Return On Investment	24.09 %
Payback Time	4.15 years

Sensitivity Study

Ionic liquid interacts with biomass based on the combination of anions and cations. ILs and their cellulose dissolving capability depend on the type of anion and its affinity to H-bond as well. Several studies described the effect of IL on biomass conversion and their extent of reaction during hydrolysis (Hashmi et al., 2017a; Usmani et al., 2020; Zabed et al., 2016). Based on the literature the effect of IL on the cellulose and hemicellulose, and water on biomass conversion are described in the table 9. The table 9 represents the information about the loading ratio of IL with cellulose and hemicellulose and IL effect on product yields. IL loading percentage shows that the variation effect the extent of reaction for cellulose and hemicellulose and checked on the develop model for palm biomass conversion. At 1% IL loading cellulose extent of reaction is 70% and 60% for hemicellulose; and the ethanol yield is 28.4%. At 2% IL loading cellulose extent of reaction is 80% and 70% for hemicellulose; and the ethanol yield is 29.23%. At 3 and 5% IL loading cellulose extent of reaction is 96% and 95% for hemicellulose; and the ethanol yield is 30.9%. Further increasing in IL loading to biomass unable have significant effect on product yield. If the product yield is increased, then the production cost will automatically be reduced. Table 9 illustrate the information of water loading percentage to total palm biomass as feed. From the table, it can be seen that the water loading percentage affect the product yield up to certain level and effect of water checked only on the developed model using SuperPro designer. At 1% water loading to total palm biomass the product yield is 4.4%, 3% loading leads to 13.2% yield, 5% loading to 21.4%, 7% loading to 29.23%, 8 and 10% loading to 30.9% yields respectively. At 8-10% loading have the most significant effect on product yield.

Table 9: Sensitivity study based on Ionic Liquid loading and water input to process.

Loading Percentage (%)	Ethanol Yield (%)
1% Ionic Liquid to total cellulose and hemicellulose	28.4
2% Ionic Liquid	29.23
3% Ionic Liquid	30.9
5% Ionic Liquid	30.9
1% water (with IL) to Total Palm biomass	4.4
3% water	13.2
5% water	21.4
7% water	29.23
8% water	30.9
10% water	30.9

CONCLUSIONS

In this report the several important aspects are considered and analysed for the ethanol production from palm biomass. Palm biomass can be considered as great resource for ethanol production due to its high cellulose content, and only 10% of palm biomass used for cooking and other purposes, and rest of the 90% palm biomass is wasted. The unused 90% palm biomass contains high percentage of cellulose which can be used for ethanol production on industrial scale and can contribute to the economy with greater impact. Ethanol from palm biomass can reduce the burden from fossil fuels and replace them based on the efficiency; and the production cost for ethanol will be very low due the availability of biomass; and only raw materials cost of biomass will be involved based on the transportation. For the ethanol production and sugar conversion and products yield; all operating conditions, reactions, cost calculations, and profitability analysis conducted based on the literature data, and the ethanol production model is developed by using SuperPro designer software, which represents the unit cost calculation of produced products and minimum selling price to ensure and predict a profitable process before entering into commercial applications, and it also can reduce the external barriers to overcome difficulties for industrial biofuels production. The total amount of lignin produced as co-product is 630 MT/day, and this amount of lignin can reduce the overall production cost by considering as revenue. Further increase in the ethanol production also possible by increasing the cellulose and hemicellulose extent of reaction during thermal and enzymatic hydrolysis. The effect of enzyme and yeast loading can be checked based on extent of reaction during enzymatic hydrolysis and fermentation which can leads to higher product yield.

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