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RESEARCH ARTICLE

Process Modeling and Techno-Economic Analysis of Xylitol Production from Oil Palm Empty Fruit Bunch (OPEFB) using SuperPro Designer®

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A B S T R A C T

OPEFB, a biomass waste derived from the crude palm oil industry, presents a promising benefit for producing xylitol through a biotechnological method. The xylitol production process encompasses several stages, including hydrolysis, fermentation, and purification, culminating in the isolation of xylitol in its crystalline form. However, the fermentation process produces impurities that necessitate meticulous separation to obtain a high purity level of xylitol crystals. In this study, the SuperPro Designer® software version 12 was employed to simulate a mass-scale xylitol production process, incorporating a membrane-based purification system that specifically integrates membrane distillation with crystallization techniques. This study is primarily focused on assessing the economic feasibility of the proposed model, with a particular emphasis on the annual operating cost (AOC). The model was designed to produce 3.00 MT/batch of xylitol as the primary product, utilizing 20 MT/batch of OPEFB in the process. Each batch required seven days for complete production, and this cycle could be repeated every three days for subsequent batches. The estimated total investment amounted to $6.00 MM, with an annual operational cost of $4.80 MM. These projections were expected to result in annual revenues totaling up to $6.84 MM. The feasibility of the developed xylitol production model was evaluated through a techno-economic analysis, which indicated a rapid payback period of 2.94 years, 29.75% gross margin, and 24.05% internal rate of return (IRR).

K E Y W O R D S

Xylitol, OPEFB, Techno-economic analysis, Modeling, SuperPro Designer®

H I G H L I G H T S

- Oil palm empty fruit bunch (OPEFB) has the potential to be converted into xylitol.
- Xylitol derived from lignocellulose biomass has numerous economic and health benefits.
- Combined membrane distillation crystallization is the most efficient purification method.
- The biotechnological xylitol production process at a mass scale was modeled using SuperPro Designer®.
- The techno-economic analysis is used to evaluate the economic performance of xylitol mass production.

INTRODUCTION

Xylitol, a sugar alcohol with five carbon atoms, is often called wood sugar due to its presence in hemicellulose-rich woods such as birch trees (Romaní et al., 2020). It is a white crystalline solid with a sweet taste, but lacks any aromatic properties. Xylitol is a sugar-free bulk sweetener that could replace sucrose and other fermentable carbohydrates. While it has a sweetness level similar to sucrose, it contains fewer calories and a lower glycemic index. Xylitol is beneficial for dental health since it is not fermented by *Streptococcus mutans* bacteria, which are known to contribute to dental caries. The demand for xylitol has been steadily increasing as it applies to a range of fast-moving consumer goods (FMCG) products, including dental care and other related derivatives (Isojärvi & Aspara, 2023). It is also widely used in the food and pharmaceutical industries (Ur-Rehman et al., 2015). Industrial bulk purchases of xylitol amount to over 125 thousand MT annually, priced at approximately $4.5-5.5 per kg, while retail prices in supermarkets can reach $20 per kg (Ravella et al., 2012). Biotechnological processes, such as fermenting hemicellulose hydrolysate from biomass, offer a viable means of xylitol production. In Indonesia, a country that holds the title of the world's largest palm oil producer, OPEFB stands out as a promising biomass source for xylitol production (Kristiani et al., 2015).

OPEFB represents the primary solid waste generated by the palm oil industry. In palm oil production, fresh fruit bunch (FFB) constitutes 23% of OPEFB (Samadhi et al., 2020). Currently, OPEFB is predominantly either utilized as an organic fertilizer or otherwise burned, leading to significant environmental challenges and negatively impacting the competitiveness and productivity of the palm oil sector. Comprised of lignocellulose, OPEFB consists of 11 – 18% of lignin, 31 – 46% of cellulose, and 22 – 25% of hemicellulose (Salam et al., 2022). These composition characteristics present the potential for OPEFB to be converted into various bio-based products, including xylitol. Lignocellulose, known for its relative abundance and cost-effectiveness, stands out as a promising renewable biomass source within the emerging global bio-economy. Through hydrolysis and fermentation processes, OPEFB could be transformed into xylitol via the conversion of xylan, a constituent of hemicellulose. Xylan can be enzymatically hydrolyzed into xylose, which is subsequently fermented into xylitol using yeast strains that possess xylose reductase (XR) enzymes, such as *Debaryomyces hansenii* and *Candida tropicalis* (Ping et al., 2013).

The biotechnological process of fermenting xylitol solution results in various impurities, including biomass, ethanol, organic acids, and other metabolic compounds that require separation (Jain & Ghosh, 2021). The selection of an appropriate separation method is crucial, considering factors such as operating costs, yield, and the desired purity of the resulting xylitol crystals. Centrifugation and ultrafiltration are commonly employed for separating biomass cells and impurities (Kresnowati et al., 2017). In cases where certain impurities are inseparable using centrifugation, ultrafiltration can effectively accomplish the separation (Salam et al., 2022). Combining centrifugation with membrane ultrafiltration shows considerable potential for separating impurities from the fermentation solution (Szczygiełda & Prochaska, 2020). Subsequently, the separated fermented xylitol solution needs to be concentrated for crystallization. Membrane distillation (MD) is a viable option for concentration due to its advantages, such as operating at moderate temperatures (typically 50-70 °C), minimizing the risk of product damage, and offering potential cost savings (Naidu et al., 2017). The crystallization stage is the final step in treating the xylitol fermentation solution, where the xylitol solution solidifies into pure crystals. Crystallization is a purification step for obtaining xylitol crystal powder (Salam et al., 2022). The crystallization process continues until a constant formation of xylitol crystals is achieved.

The economic aspect plays a crucial role in the mass production of xylitol. Process simulation is commonly employed to assess the economic viability of xylitol production processes. In this study, the simulation and evaluation of the xylitol production process were conducted using the SuperPro Designer® V.12 software. This software allows for the comprehensive analysis of various factors, including process parameters, equipment selection, energy requirements, and costs, providing valuable insights into the techno-economic feasibility of the production plant. Process simulation offers several advantages, and it allows for a systematic evaluation of different process configurations and the optimization of operating conditions to enhance efficiency and reduce costs, as well as identifying potential bottlenecks, areas for improvement, and opportunities for process integration. Furthermore, process simulation enables a thorough examination of the economic viability of the production plant by estimating operating costs, revenues and profitability indicators such as payback period, gross margin, and internal rate of return (IRR). By conducting process simulation and techno-economic analysis, informed decisions can be made to assess the feasibility of implementing the xylitol production process facility.

METHODOLOGY

Production of xylitol crystals

The production of xylitol crystals involved several steps: The hydrolysis of OPEFB, fermentation of the hydrolyzate, and purification of the fermentation broth using centrifugation and ultrafiltration (Martinez et al., 2022). Another purification method combined membrane distillation and cooling batch crystallization (Martínez et al., 2015; Salam et al., 2022). The xylitol production process involved several distinct steps. In the pretreatment stage, a 20 MT mass of OPEFB underwent grinding and sieving to reduce its size, followed by washing and drying to achieve a water content of 12%. The dried OPEFB was then mixed with a buffer solution for further hydrolysis using xylanase enzyme at 50 °C and 150 rpm for 48 hours. In the fermentation step, the hydrolyzed OPEFB underwent sterilization and filtration to obtain a xylose-rich solution fed into the

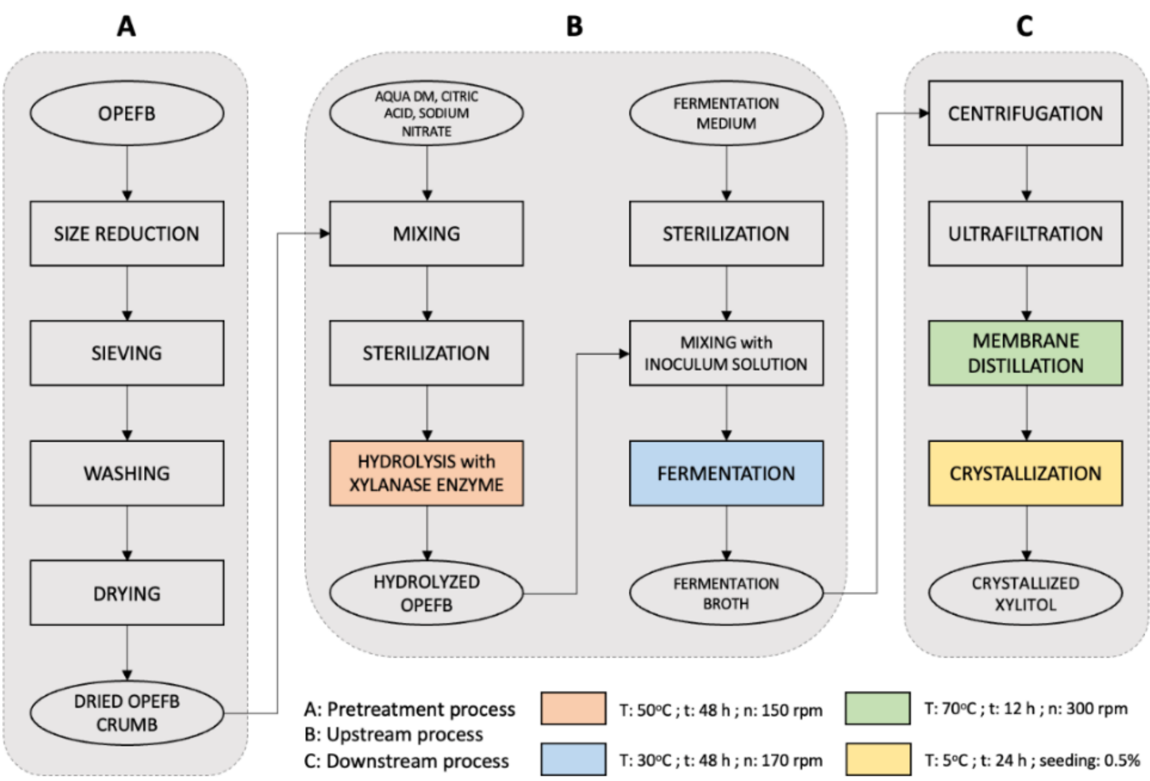

Figure 1. Block flow diagram of xylitol production from OPEFB.

fermentor. The fermentation process lasts 48 hours using *Debaromyces hansenii* at 30 °C and 150 rpm, with an assumed conversion rate of 80% xylose to xylitol. The fermentation broth was subjected to centrifugation, microfiltration, ultrafiltration, and membrane distillation processes. The submerged membrane distillation process involved heating the feed tank, applying a shear force on the membrane surface, and condensing the vapor in the permeate tank (Julian et al., 2020). The concentrated retentate was then crystallized through a cooling batch crystallization method at a chilling temperature of 5 °C. Figure 1 illustrates the block flow diagram of the xylitol production process from OPEFB.

Process modelling and techno-economic analysis

A conceptual model for xylitol production was developed and economically assessed. The model incorporated information from technical literature and previous experiments to estimate the necessary raw materials, equipment capacities, utility requirements, capital investment, and production costs. Manual registration and definition were conducted for the components unavailable in the software's database. The registered components for this model can be found in Table 1.

Table 1. Registered component.

Component	Full Name	Formula
Cellulose	Cellulose	$(C_6H_{10}O_5)n$
Hemicellulose	Hemicellulose	$C_5H_{10}O_5$
Lignin	Lignin	$C_{81}H_{92}O_{28}$
Water	Water	H_2O
Xylose	Xylose	$C_5H_{10}O_5$
Xylanase	Xylanase Enzyme	Xylanase
Xylitol Crystal	Xylitol Crystal	$C_5H_{12}O_5$
Xylitol	Xylitol Solution	$C_5H_{12}O_5$
Microbes	*Debaryomyces hansenii*	*Debaryomyces hansenii*
Yeast	Bakers Yeast Extract	$C_{19}H_{14}O_2$
Peptone	Peptone	$C_{13}H_{24}O_4$
Ammonium Sulfate	Ammonium Sulfate (aq)	$(NH_4)2SO_4(aq)$
Iron Sulfate	Iron (II) Sulfate (aq)	$FeSO_4(aq)$
Manganese Sulfate	Manganese (II) sulfate (aq)	$MnSO_4(aq)$
Citric Acid	Citric Acid	$C_6H_8O_7$
Sodium Nitrate	Sodium Nitrate	$NaNO_3$
Potassium Phosphate	Potassium Di-hydrogen Phosphate	KH_2PO_4
Potassium Iodide	Potassium Iodide	KI

The process was divided into three sections to facilitate analysis and improve visualization: Pretreatment, fermentation, and purification. Unit processes were carefully selected and arranged sequentially, with connections established through streamlines. The comprehensive process flow diagram can be seen in Figure 2.

For the simulation, data regarding operating conditions for each unit operation and the overall production process were obtained from various sources, such as references, trial experiments, and the SuperPro Designer. The obtained data were compared with experimental results from previous laboratory studies. The key variables assessed in the validation process were the yield of fermented xylitol and the yield of xylitol crystals produced. Once the simulation results have been validated, an economic report was

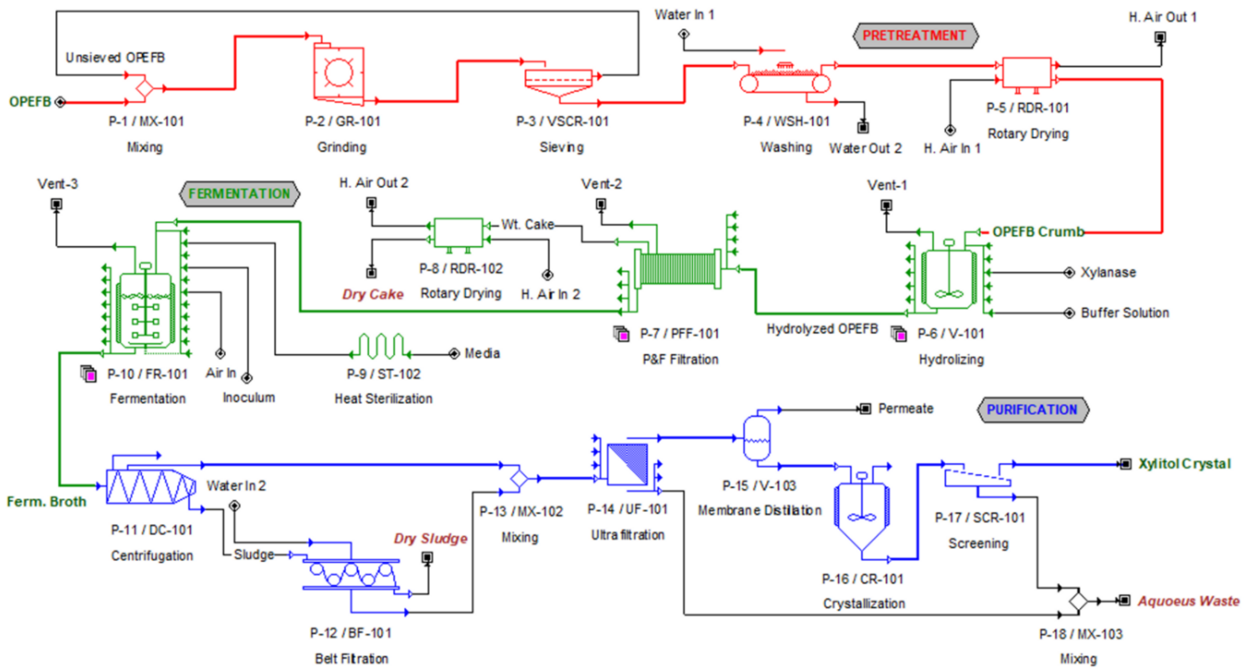

Figure 2. Process flow diagram of xylitol production in SuperPro Designer®.

generated. This report included important financial indicators such as gross margin, return on investment, payback time, internal rate of return, and net present value.

RESULTS AND DISCUSSION

Process model evaluation

The model was evaluated based on its ability to produce the main product, in this example, xylitol. SuperPro Designer® was able to generate comprehensive data, including materials and streams report, equipment data, scheduling of unit operations, waste evaluation through environmental impact report, and economic evaluation report. Data on the overall process, which consists of batch time and throughput, is presented in Table 2.

Table 2. Overall process data.

Batch Size	3021.25 kg MP
Recipe Batch Time	164.88 h
Recipe Cycle Time	51.44 h
Number of Batches per Year	151.00
Annual Operating Time	7880.45 h
Annual Throughput	456208.32 kg MP/year

The batch process model demonstrates the capability to handle a 20 MT/batch of OPEFB, producing 3 MT/batch of xylitol. The batch process duration spanned seven days. The plant, which operates for 11 months annually, follows a cycle time of approximately 51.44 hours, meaning that a new batch commences every three days. Consequently, the plant completes approximately 151 batches per year. As a result, the batch process operates for 7880.45 hours annually, yielding an output of 45.6 MT of xylitol per year.

The unit operations were operated at various time operation. Equipment scheduling was necessary to observe through the Equipment Occupancy Chart (EOC). Time operations in each type of equipment were set up related to the previous experiment that has been conducted. The EOC provided information on the batch period needed according to the respective time operations in each type of equipment. Therefore, the equipment scheduling in the respective batch period could be observed through the EOC. The EOC for four consecutive batches is presented in Figure 3, with each color representing a different batch.

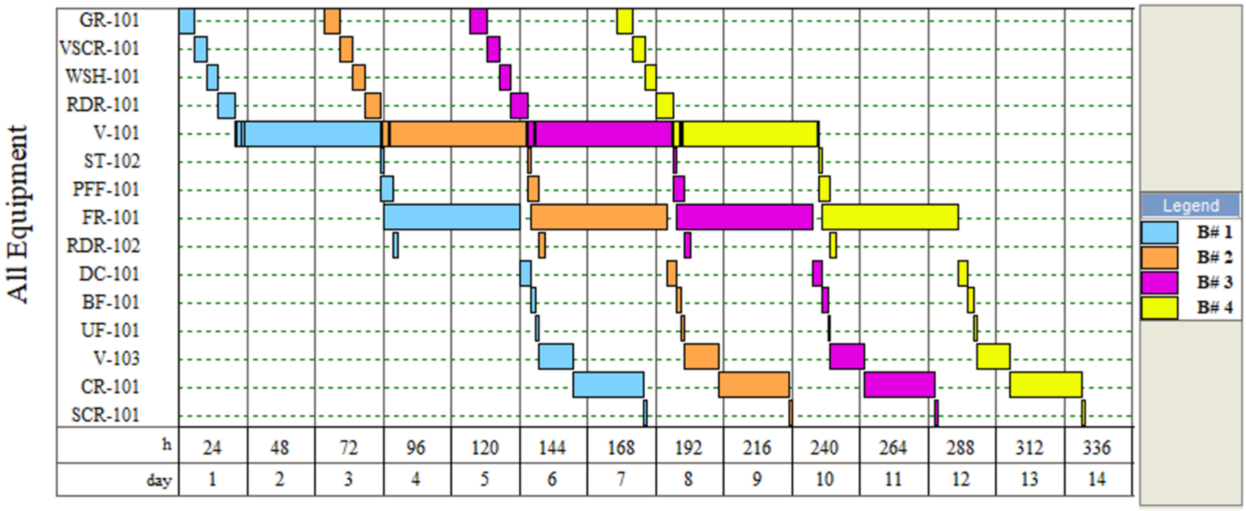

Figure 3. Equipment occupancy chart.

The mixing tank (V-101) in the hydrolyzing section exhibited the most extended duration of equipment occupancy, lasting 52 hours. Its purpose is to facilitate the enzymatic hydrolysis process, converting hemicellulose (xylan) into xylose. Previous research (Nurdin et al., 2021) determined that the optimal hydrolysis time is 48 hours. The fermentation section's bioreactor tank (FR-101) ranked second in equipment occupancy, requiring 48 hours per batch. This section converts xylose produced during hydrolysis into xylitol. Experimental findings from Mardawati et al. (2022) indicated that a 48-hour operating time is necessary to produce xylitol. The subsequent purification section comprises 12 hours for membrane distillation and 24 hours for cooling batch crystallization.

Materials and streams were also observed to identify the changes in OPEFB form, particularly in unit operations. The changes of 4.7 MT xylan (hemicellulose) into 4.3 MT xylose occurred in the hydrolyzing section (V-101), while the changes of this xylose into 3.4 MT xylitol resulted in the fermentation section (FR-101). Furthermore, the xylitol solution was crystallized using batch cooling crystallization, and 89.77 % crystal yield with absolute purity was obtained. Table 3 shows changes in OPEFB form and flow rate to form xylitol crystals.

Analyzing substrate consumption and product formation trends based on the process modeling results is necessary to obtain an accurate visualization of the rate of xylitol formation. The hydrolyzing and fermentation operations were crucial for converting the substrate into the desired product. The formation trend of xylitol and the consumption of xylan and xylose can be observed in Figure 4.

Hydrolysis is a process that involves the separation of lignin, cellulose, and hemicellulose, with the specific aim of converting hemicellulose into xylose. Based on the given reference, enzymatic hydrolysis was identified as a suitable method for obtaining xylose (Judiawan et al., 2019). The resulting xylose obtained from hydrolysis is crucial for the subsequent fermentation process. In fermentation, an industrial bioreactor tank (FR-101) converts xylose into xylitol using the *D. hansenii* microorganism. The conversion of xylose into xylitol during fermentation is not comprehensive. The reference suggests that approximately 83% of the xylose is successfully converted into xylitol. At the same time, the remaining portion may produce byproducts such as ethanol and acetic acid (Mardawati et al., 2022). These byproducts and any unreacted components contribute to the impurities in the fermentation broth solution.

Table 3. Xylitol formation rate.

No.	Types of Feed	Related Unit Process	Flow rate (Kg/batch)		
			Xylan	Xylose	Xylitol
1	OPEFB Crumb	RDR-101	4753.98	0.00	0.00
2	OPEFB Hydrolyzate	V-101	475.40	4276.92	0.00
3	OPEFB Hydrolyzate Filtrate	PFF-101	47.54	4063.07	0.00
4	Fermentation Broth	FR-101	47.54	841.69	3365.56
5	Purified Ferm. Broth	MX-102	17.11	841.16	3363.45
6	UF Permeate	UF-101	9.29	686.09	3356.94
7	MD Retentate	V-103	9.29	686.09	3356.94
8	Crystallization Product	CR-101	9.29	686.09	3021.25
9	Sieved Crystals	SCR-101	0.00	0.00	3021.25

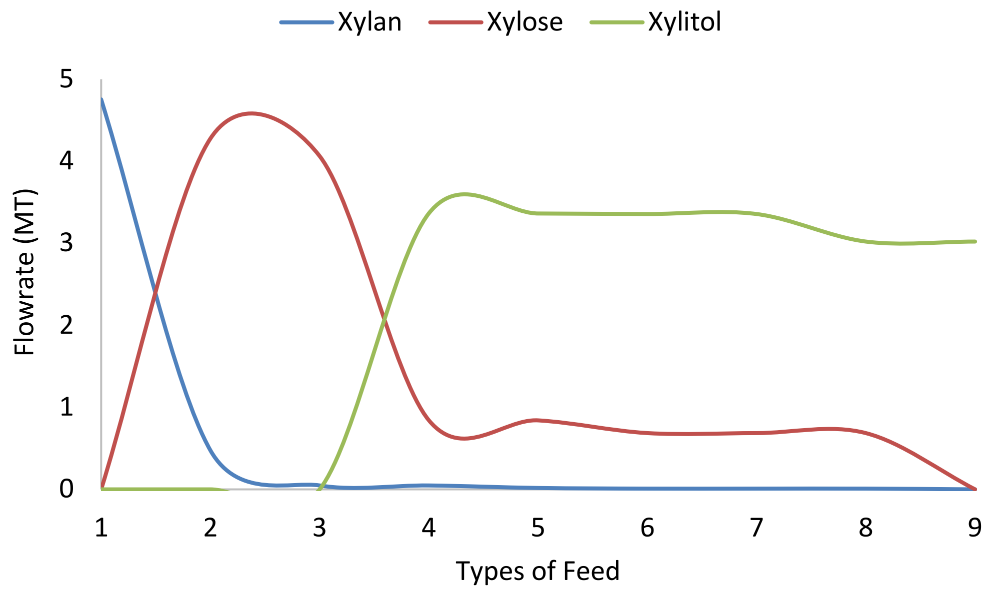

Figure 4. The trend of xylitol formation.

Purification as a part of downstream processing was needed in this process model to get a higher purity level of xylitol and waste valorization. Therefore, suitable downstream processing techniques are essential to consider in regards to operating cost, product yield, sustainability, and environmental impact (Salam et al., 2022). The waste from this plant was solid waste consisting of dry cake, dry sludge, and aqueous waste. The dry cake waste as the throughput from the hydrolyzing section and dry sludge from the centrifuge section contains rich cellulose that could be utilized as a livestock feed material (Yanti et al., 2021). While aqueous waste has water as a significant component could be assumed as unhazardous waste and is accessible to process before releasing to the environment. The detailed compositions of solid and aqueous waste are shown in Figure 5.

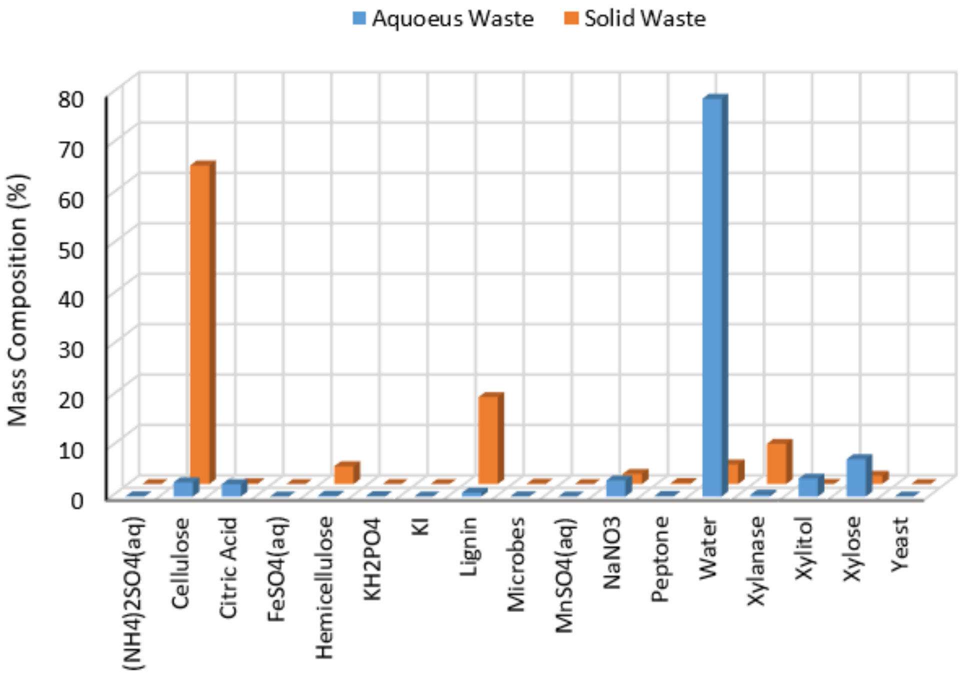

Figure 5. Compositions of aqueous waste and solid waste.

Most solid wastes in this process are derived from the throughput streams of the hydrolyzed OPEFB filtration and the solid stream from the centrifuge decanter. The filtration process using plate-and-frame filters, followed by centrifugation, effectively removes a significant percentage of cellulose, lignin, and biomass, as indicated in the chart. The sludge obtained from the centrifuge undergoes washing to dilute any remaining xylitol, before being combined with the supernatant stream for further processing through ultrafiltration. Ultrafiltration using UF membranes enhances the separation process by eliminating residual impurities from the centrifugation step (Kresnowati et al., 2017).

A typical approach involves multiple-stage evaporation to concentrate the xylitol solution before crystallization. However, this method is not cost-effective due to the high temperatures required for solvent removal, which may potentially harm the main components in the solution. As an alternative, membrane distillation (MD) offers a lower temperature requirement and reduced energy consumption for solvent removal (Yadav et al., 2021). Combining MD with crystallization (MDC) yields high-purity xylitol crystals and necessitates 3.7 kW of electricity, 3.6 MT/h of steam, and 0.775 MT/h of freon. The performance of MDC has demonstrated promising outcomes for the downstream processing of microbial xylitol (Martínez et al., 2015).

Techno-economic analysis

The economic aspect holds a big significance in the analysis of the process model. SuperPro Designer® facilitates a comprehensive evaluation of the economic aspects by generating a detailed economic evaluation report encompassing various cost components such as raw materials, labor, facilities, laboratory, waste, utilities, and consumables. The analysis involves calculating the annual operating cost (AOC) and assessing key indicators, including gross margin, return on investment (ROI), payback time, internal rate of return (IRR), and net present value (NPV). In this process model, the projected annual production of xylitol crystals amounted to 456 MT. The AOC calculation is essential in understanding the impact of operating factors on the overall product cost. For this particular plant, the calculated AOC amounted to $4,807,058. A detailed breakdown of the number is provided in Figure 6.

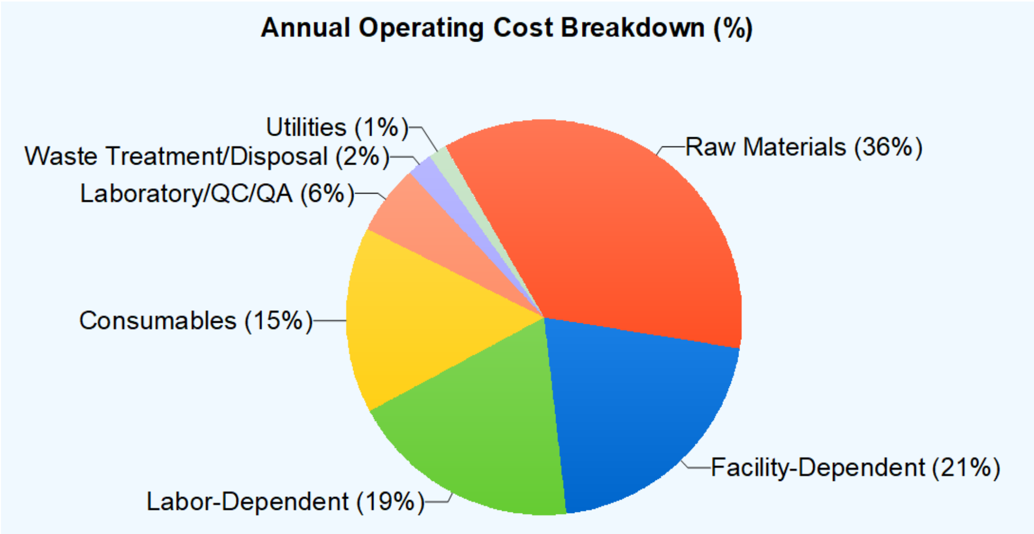

Figure 6. Annual Operating Cost (AOC).

Raw material cost contributed the most significant percentage to the annual operating cost (AOC), encompassing expenses for OPEFB, buffer solution, xylanase enzyme, fermentation media, and microbes/inoculum. The estimated prices for these raw materials were obtained through surveys of chemical stores in Indonesia. The second highest cost component relates to facility-dependent costs, comprising the equipment or unit operations utilized in the process model and installation cost, contributing 21% to the AOC. The equipment prices were acquired through an online survey of manufacturing companies in China and Indonesia. Labor cost covers wages for operators, laboratory employees, and supervisors overseeing critical processes. Consumables cost consist of membrane for UF and MD process and cartridge in the filtration process. Laboratory-dependent costs account for 6% of the AOC. Waste treatment costs, including dry cake, dry sludge, and aqueous waste disposal, represents a minor portion of 2% of the AOC. Among the utility costs, electricity accounts for the highest proportion due to its intensive usage during the extended fermentation period for agitation and temperature control. The analysis considered standard electric power, steam, and freon, with their respective prices based on the default settings in SuperPro Designer® software. Further details data regarding the equipment, materials, and utilities used in this process model can be found in Table 4.

By default, SuperPro Designer® provides estimated prices for components such as equipment, material, labor, tax, utility, and related facility. However, these prices can be adjusted based on specific process conditions and the plant's location. Many prices for unit operations were obtained from manufacturing companies in China and Indonesia. Determining a supplier involved considering distribution time, cost, capacity, and quality factors. China is geographically close to Indonesia, which reduces distribution time, and Chinese manufacturers can produce high-capacity equipment at competitive prices without compromising quality.

On the other hand, chemical materials were purchased locally in Indonesia since the quantities required were relatively small. OPEFB, as the primary raw material, is abundantly available in Indonesia as it is considered waste by the palm oil industry. Therefore, it can be easily obtained at a lower cost. Regarding utilities, steam was used for heat energy supply, freon was employed for temperature control in specific unit operations, and electricity was the primary power source for operating the unit operations. The number of utilities required depends on the specifications of the equipment. All of this data is used to calculate the economic performance of the model. The profitability analysis results are presented in Table 5.

Table 4. Equipment, materials, and utilities (estimated cost in 2023).

Equipment specification and cost				
Unit Operations	**Required Capacity (MT)**	**Estimated Survey Data**		
		Capacity	**Min. Power (KW)**	**Price ($/unit)**
Grinder	22.22	4,000 kg/h	55.00	1,000.00
Vibrating Screen	22.22	5,000 kg/h	2.00	2,000.00
Washer	20.00	5,000 kg/h	1.50	5,000.00
Rotary Dryer	24.81	115 MT/h	4.50	5,000.00
Hydrolyzer	36.81	20,000 L	7.50	25,000.00
Plate & Frame Filter	36.81	100 m2	5.00	15,000.00
Retort Sterilizer	2.00	1,950 L/h	5.00	10,000.00
Fermentor	26.97	15,000 L	15.00	50,000.00
Decanter	26.97	7,500 L/h	5.00	30,000.00
Belt Filter	2.74	2,000 mm	2.60	10,000.00
Ultrafiltration (UF)	45.53	50 m2	5.50	45,000.00
Membrane Distillation (MD)	44.58	165 L	1.50	40,000.00
Crystallizer	12.84	40 m3	3.70	5,000.00
Materials cost				
Bulk Material	**Unit Cost ($)**	**Annual Amount (kg)**		**Annual cost ($)**
Citric Acid	0.600		43,174	25,904
Ferm. Medium	0.010		302,000	2,049
Microbes	0.010		1,696	17
$NaNO_3$	0.500		91,745	45,872
OPEFB	0.010		3,020,000	15,100
Peptone	1.000		5,656	5,656
Water	0.001		8,628,020	8,628
Xylanase	10.000		161,902	1,619,022
Yeast	1.900		283	538
Utilities cost				
Utility	**Unit Cost ($)**	**Annual Amount**	**Ref. Units**	**Annual cost ($)**
Std. Power	0.100	671,763	kW-h	67,176
Steam	0.260	6,932	MT	1,941
Freon	0.150	15,343	MT	2,301

The total capital investment for this project amounted to $6 million, which included the cost of purchasing equipment, direct fixed capital, working capital, start-up expenses, and validation costs. On the other hand, the operational costs encompassed components such as materials, facility-dependent costs, labor-dependent costs, laboratory expenses, consumables, utilities, and waste disposal, totaling to $4.8 million. Considering that the selling price of xylitol crystals was $15 per unit, the projected annual revenue from the production of xylitol crystals was estimated to be at $6.8 million. With these financial figures in mind, it is evident that this process model demonstrates feasibility and offers promising economic prospects. The payback period for the initial investment was expected to be approximately 2.94 years, indicating a relatively rapid return on investment.

Additionally, the model exhibited a gross margin of 29.75%, reflecting the profitability of the xylitol production process. The return on investment (ROI) is projected to reach 34.04%, further underscoring the project's economic viability. Moreover, the internal rate of return (IRR) was estimated to be 24.05%, indicating a favorable rate of return considering the project's cash flow. Overall, this process model yields economic benefits and ensures a promising material and energy balance, making it an attractive venture from both financial and operational perspectives.

Table 5. Executive summary of profitability analysis.

Total Capital Investment	6,018,000 $
Operating Cost	4,807,000 $/yr
Revenues	6,843,000 $/yr
Batch Size	3,021.25 kg MP
Cost Basis Annual Rate	456,208 kg MP/yr
Unit Production Cost	10.54 $/kg MP
Unit Production Revenue	15.00 $/kg MP
Gross Margin	29.75 %
Return On Investment	34.04 %
Payback Time	2.94 years
IRR (After Taxes)	24.05 %
NPV (at 7.0% Interest)	8,260,000 $

CONCLUSION

The process simulation conducted using SuperPro Designer® V.12 software provided valuable insights into the key parameters, equipment selection, energy requirements, and costs associated with the production plant. The production of xylitol crystals was achieved with high efficiency and purity by combining hydrolysis, fermentation, and purification techniques. The purification stage, including centrifugation, ultrafiltration, and membrane distillation, effectively separated impurities from the fermentation broth, resulting in a xylitol solution that was subsequently crystallized through cooling batch crystallization. The process evaluation results revealed that the batch process model effectively handled a 20 MT/batch of OPEFB, producing 3 MT/batch of xylitol. The economic analysis conducted as part of the techno-economic assessment revealed promising results for the xylitol production process. Key financial indicators such as gross margin, return on investment, payback time, internal rate of return, and net present value were estimated, demonstrating the economic viability of implementing the xylitol production facility. The findings of this study provide a foundation for further research and development in the field of bio-based products, highlighting the importance of considering both technical and economic aspects in the design and optimization of bioprocesses.

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