Techno-economic analysis of furfural production with various pretreatment of oil palm empty fruit bunches using SuperPro Designer

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Abstract. Oil palm empty fruit bunches (OPEFB) are solid wastes that can be processed into several chemicals, one of which is furfural. Furfural can be used as a solvent and intermediate compound in many chemical industries. Nowadays, furfural needs in Indonesia are fulfilled through import, especially from China. Therefore, developing a furfural plant in Indonesia is required to fulfill the needs for furfural in Indonesia and surrounding countries. Based on that necessity, this study provides the preliminary study and simulation of furfural production from OPEFB by three kinds of pretreatment methods: soaking in aqueous ammonia (SAA), steam explosion (SE), and ammonia fiber expansion (AFEX). Simulation is conducted using SuperPro Designer Academic License to get the plant’s mass & energy balance and economic parameters. The plant will be built in Kawasan Industri Dumai, Pelintung, Riau. Then, by assuming 7920 hours annual operation time and 2000 kg OPEFB/h input rate, the simulations showed that furfural production with AFEX pretreatment is more economically feasible than with SAA and SE pretreatment. The value of profitability parameters as follows: Internal Rate of Return (IRR) = 49.77%, Net Present Value (NPV) at i = 9.6% = USD 39,210,000, and payback time = 1.75 years.

1. Introduction

Indonesia, being the world leader in the production of crude palm oil and, at the same time, the solid waste in the form of oil palm empty fruit bunch (OPEFB) [1]. The lignocellulose materials in OPEFB can be converted into different value-added materials such as formic acid, levulinic acid, and furfural [2-4]. Furfural can be used as a solvent to separate saturated and unsaturated compounds in crude oil industries. It can also be used as an intermediate compound in other chemical industries, such as paint industries, synthetic rubber industries, and others [5]. Although the need for furfural continues to increase, Indonesia does not produce furfural. In 2019, the need for furfural in Indonesia reached 666 tons [6]. Therefore, developing a furfural plant in Indonesia is required to fulfill the needs of furfural in Indonesia.

There are some pretreatment methods for converting OPEFB into furfural, including physical, chemical, physicochemical, and biological pretreatment. Each method has its advantages and disadvantages [7]. This paper aims to compare the effectiveness and economics of three different
OPEFB pretreatments for furfural production, i.e., Aqueous Ammonia (SAA), Steam Explosion (SE), and Ammonia Fiber Expansion (AFEX).

2. Methods

The OPEFB was pretreated with three different methods of pretreatment, soaking in aqueous ammonia [8], steam explosion [9], and ammonia Fiber expansion [10]. These studies were done in prior research and used as primary data in this research.

The Soaking in Aqueous Ammonia (SAA) method is a chemical-based pretreatment method. This process intends to eliminate lignin and increase cellulose’s porosity to increase the cellulose conversion to glucose in hydrolysis. The SAA pretreatment is chosen because of its simple process and high selectivity to maintain hemicellulose and eliminate lignin [11]. This method’s procedure is by soaking OPEFB in ammonia liquid (15%) at 70 °C and suppressing it for 14 hours [8]. During this process, ammonia will actively open and break the lignocellulose structure to release more lignin. After the SAA pretreatment, lignin separates selectively from biomass, so it is expected that only the cellulose and hemicellulose remained [11]. The overall simulation flow sheet for SAA pretreatment is provided in Figure 1 below.

Steam power has the potential to degrade (thereby pretreat) the complex structure of lignocellulosic biomass. In steam pretreatment, the biomass is simultaneously treated with high pressure and high temperature steam of 140-260 °C, for a few minutes to several minutes. Steam pretreatment has been reported to be efficient in partially hydrolyzing hemicelluloses, modifying the lignin, increasing access to the surface area, decreasing cellulose’s crystallinity, and its degree of polymerization [12]. In this process, dry OPEFB was exploded in the reactor under saturated steam conditions at a temperature of 140 °C, the pressure of 2.8 bar, and a retention time of 15 minutes for explosion reactions [9]. The overall simulation flow sheet for SE pretreatment is provided in Figure 2 below.

![Figure 1. Simulation Flowsheet of Furfural Production using SAA Method](image-url)
Ammonia Fiber Expansion (AFEX) is an ammonia-based pretreatment process that has shown tremendous promise to cost-effectively reduce the recalcitrance of lignocellulosic biomass to enzymatically catalyzed deconstruction into fermentable sugars [13]. AFEX pretreatment uses about one kg of anhydrous ammonia per kg of biomass at moderate temperatures (e.g., 90–100 °C) and high pressures (e.g., 250–300 psi) for approximately 30 min followed by the release of pressure resulting in biomass disruption [14]. The quick expansion of liquid ammonia causes swelling and physical interference of lignocellulose fiber and partial cellulose crystallinity reduction. This method can modify or decrystallize the cellulose and lignin fraction effectively [15]. In this process, the OPEFB was loaded into a high-pressure stainless steel reactor, and the reactor lid was closed. Anhydrous liquid ammonia was added to OPEFB in the ratio of 2:1 (dry weight basis), and the residence time was 30 min at 102 °C and 325 psi [10]. The overall simulation flow sheet for AFEX pretreatment is provided in Figure 3 below.

After creating a simulation flowsheet, the next step is to complete the equipment data and specifications that are needed for the equipment. All costs, including raw materials, labor, utilities, and
other related costs, are taken into account meticulously since the techno-economics analysis will be done right after the simulation. In the end, each variation will be compared economically and determined which one is more profitable.

3. Results and Discussion

The process runs continuously with an annual operating time of 330 days. The simulation is done by using SuperPro v9.5 software. Several processes are used to produce furfural from the OPEFB, including size reduction, pretreatment, hydrolysis, and purification.

The production capacity of this furfural plant is 15.84 tons of OPEFB per year, and the plant is located at Kawasan Industri Dumai. This industrial estate is in Dumai City, Pelintung, Riau. This location has an area of 1000 hectares. Kawasan Industri Dumai has been equipped with docks, power plants, oil bulking terminals, tanks, water treatment plants, and sewage treatment. The plant location is provided in Figure 4.

![Figure 4. Proposed Plant Location in Dumai City, Pelintung, Riau Province](image)

3.1. Pretreatment Technology Analysis

To evaluate the most suitable furfural production process, pretreatment performance, the yield, number of units, solvent, utility, and waste were compared. AFEX pretreatment gives the highest hemicellulose recovery, so it also gives the highest product yield, 14.8%, compared with SAA and SE, which gives a yield of 12.5% and 12.8%. However, AFEX pretreatment requires more solvents than SAA pretreatment because it used anhydrous ammonia. Meanwhile, SE pretreatment gives the lowest number of units because there is no ammonia recycling process. SE pretreatment also gives the highest utilities needed and waste production. The performance of each simulation is shown in Table 1.

| Aspects          | Pretreatment Method |
|------------------|---------------------|
|                  | SAA    | SE    | AFEX  |
| Pretreatment Performance | 100   | 100   | 100   |
|                  | 82     | 84    | 97    |
|                  | 53     | 90    | 99    |
| OPEFB (MT/year)  | 15.84  | 15.84 | 15.84 |
| Furfural (MT/year) | 1.98  | 2.03  | 2.34  |
| Yield (p/s)      | 12.5   | 12.8  | 14.8  |
| Number of Units  | 17     | 15    | 17    |
### 3.2. Economic Analysis

There are two types of costs: total capital Investment (TCI) and operational expenditure (OPEX). TCI is the sum of all fixed capital costs, and the working capital cost calculated. The summary for the calculation is shown in Table 2.

| Aspects                      | Pretreatment Method |
|------------------------------|---------------------|
|                              | SAA    | SE   | AFEX  |
| Solvent (MT/year)            |        |      |       |
|                              | 22,640 | -    | 25,055|
| Utility                      |        |      |       |
| Steam (MT)                   | 107,675| 526  | 12,914|
| High pressure steam (MT)     | 571,164| 820,627| 675,610|
| Cooling water (MT)           | 3,972,453| 4,090,974| 4,568,017|
| Chilled water (MT)           | 11,154,093| 20,290,480| 2,905,226|
| Waste                        |        |      |       |
| Solid (MT)                   | 3,056  | 4,409| 4,897 |
| Liquid (MT)                  | 383.84 | 457.64| 333.94|

OPEX is a cost incurred by a company to carry out production and other supporting activities each year. OPEX components are raw materials (OPEFB, ammonia, sulfuric acid, water), labor, auxiliary facilities, laboratories, waste treatment, and utilities. OPEX value obtained annually for SAA pretreatment is USD 119,695,000, which is dominated by the raw materials' cost. OPEX values of SE pretreatment is USD 42,150,000, which are dominated by the utility cost. Meanwhile, the OPEX value of AFEX pretreatment is USD 95,475,000, which is dominated by the raw materials' cost. The summary of OPEX for three different methods of pretreatment is shown in Table 3.

| Operational Cost               | SAA      | SE       | AFEX   |
|--------------------------------|----------|----------|--------|
| Raw Materials                  | 73,086,000| 5,434,000| 80,981,000| 84.82 |
| Labor-Dependent                | 700,000  | 615,000  | 704,000 | 0.74  |
| Facility-Dependent             | 1,381,000| 1,189,000| 1,106,000| 1.16  |
| Laboratory/QC/QA               | 366,470  | 315,652  | 293,427| 0.11  |
| Waste Treatment/Disposal       | 31,879,000| 14,975,000| 642,000| 0.67  |
| Utilities                      | 12,544,000| 19,844,000| 11,936,000| 12.50 |
| **TOTAL**                      | **119,695,000**| **42,150,000**| **95,475,000**| **100.00** |

The three variations of pretreatment of furfural production from OPEFB can be considered economically feasible from the profitability parameter values. This can be seen from the value of Net Present Value (NPV), which is greater than zero, and the value of Internal Rate of Return (IRR) > Weighted Average Cost Capital (WACC = 9.6). Meanwhile, furfural production from OPEFB
with AFEX pretreatment is more economical than furfural production with SAA or SE pretreatment. This can be seen clearly from the better value of AFEX pretreatment’s profitability parameters: greater ROI, NPV, and IRR values and shorter payback periods in Table 4.

| Pretreatment                          | IRR (%) | NPV (USD) | ROI (%) | Payback Time (years) | Revenue (USD/year) |
|---------------------------------------|---------|-----------|---------|----------------------|--------------------|
| Soaking in Aqueous Ammonia            | 27.42   | 20,096,000| 30.55   | 3.27                 | 127,925,894        |
| Steam Explosion                       | 27.42   | 11,900,000| 33.32   | 3                    | 46,893,759         |
| Ammonia Fiber Expansion               | 49.77   | 39,210,000| 57.02   | 1.75                 | 108,544,456        |

3.3. Sensitivity Analysis

Project feasibility is also evaluated from its sensitivity to key variables, such as selling price, OPEFB price, and the production capacity. The sensitivity analysis will use NPV, IRR, and payback time to determine the complete analysis. Figures 5-7 show the effect of changes in selling price, OPEFB price, and the production capacity to NPV, IRR, and payback time value. It was found that production capacity has the most significant influence on the NPV, IRR, and payback time value. Both selling price and OPEFB price do not affect the project as much as the production capacity, showing less risk on these parameters.

Figure 5. Sensitivity Graph of Net Present Value (NPV)
4. Conclusion
This study showed that furfural production with AFEX pretreatment is more economically feasible than with SAA and SE pretreatment by the value of profitability parameters as follows: Internal Rate of Return (IRR) = 49.77\%, Net Present Value (NPV) at \( i = 9.6\% \) = USD 39,210,000, and payback time = 1.75 years. This study also found that the most sensitive parameter that affects the NPV, IRR, and payback time significantly is production capacity.

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