Techno-economic analysis of furfural purification process from hydrothermal hydrolysis products of oil palm empty fruit bunches using distillation and extraction methods

G Suyuditomo¹, I Karimah¹, A F P Harahap¹, M Y A Ramadhan¹, J R H Panjaitan², M Sahlan¹, H Hermansyah¹ and M Gozan¹

¹Department of Chemical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus Baru UI, Depok, 16424, Indonesia
²Chemical Engineering Program, Institut Teknologi Sumatera, Lampung 35365, Indonesia
*E-mail: mrgozan@gmail.com

Abstract. Furfural is a high-selling compound produced from cellulose and hemicellulose conversion, and the level of demand in Indonesia is still high. This research examines the economic process design and calculation of furfural production made from TKS by varying the purification method with the distillation method and the toluene extraction method using SuperPro Designer 9.5 software. Furfural purification uses two methods, namely furfural purification using toluene extraction scheme and distillation scheme. Two plant location recommendations can be chosen based on the factory's location close to the buyer, namely in Cilacap, and the plant's location close to the supplier, namely Banten. Based on the economic calculation results, the toluene extraction purification scheme with an IRR value of 26.02% is more profitable even though its purity is 99.95% compared to the distillation purification scheme with an IRR of 25.86% even though its purity reaches 99.96%. The two recommendations for the location of the calculation of the economic payback period owned by the two locations almost the same. Cilacap, which has an NPV value of 89,739,000 $, is more profitable than Banten, which has an NPV value of 87,430,000 $.

1. Introduction

Indonesia is the largest palm oil producer in the world. Indonesia produces 47.2 million tons of palm oil in 2019 [1]. From 2015 to 2019, palm oil production's compound annual growth rate is 7.7% each year. The increasing area of palm oil plantations is also accompanied by the increasing palm oil processing industry player.

Therefore, the high production of palm oil causes a lot of palm oil waste produced. Every 1 ton of fresh oil palm fruit bunches produces 23% of oil palm empty fruit bunches (OPEFB), 6.5% of shells, 4% of solid wet decanter (palm oil sludge), 13% of fibbers, and 50% of liquid waste [2]. OPEFB is a by-product of palm oil processing, which is still limited in use as fertilizer and as a medium for the growth of fungi and plants. In Indonesia, 82% of furfural needs come from the lubricating oil industry, and 18% come from other industries such as synthetic rubber [3].

Palm oil industry waste contains high organic matter. Thus, OPEFB has the potential to be a source of cellulose biomass with a high abundance and renewable nature. OPEFB is a waste that can be converted into various chemical compounds, including furfural [4-9]. Furfural is a selective solvent for taking aromatic compounds, olefins, and sulfur from petroleum. However, Indonesia still relies on
furfural imports from China. According to furfural import data up to November 2019, the quantity of furfural imports in Indonesia reaches 44.43 tons per month [10].

Referring to the high demand for furfural, further review is needed related to furfural purification methods with maximum yield and profit values. In addition to variations in the purification method, variations in the location of furfural processing plants are also carried out to choose a more favorable location for raw material supply and furfural distribution.

The aim of this paper is designing the production process configuration to build an OPEFB biomass-based furfural plant, comparing the effectiveness and economics of the furfural purification process of OPEFB between distillation and extraction methods, and comparing the economics of furfural factories at locations close to raw materials and locations close to consumers.

2. Methods
Several steps need to be conducted to make this plant design, including process selection, process design, equipment sizing, hazard analysis, and economic analysis. The process selection is made by referring to preliminary research, and it is ensured that the process is feasible economically and thermodynamically [7-9]. In this furfural purification process, all physical and chemical processes are studied thoroughly for each variation to maximize the purification process, both distillation and extraction using toluene as solvent. The process design stage begins with the process concept in the form of a block flow diagram, which is considered the most important step. The block flow diagrams of the whole furfural purification plant are illustrated in Figure 1 for distillation and Figure 2 for extraction.

![Block flow diagram of furfural purification process using a distillation method](image-url)

**Figure 1.** Block flow diagram of furfural purification process using a distillation method
The next step is to complete the equipment data and specifications needed for equipment and space sizing. All costs, including raw materials, labor, utilities, transportation, and other related costs, are taken into account meticulously since techno economics analysis will be performed right after the simulation. First, each variation will be compared economically and determined which one is more profitable. After determining the most profitable purification process, plant location variation is conducted, once again, to determine which one is more profitable. The production capacity of this furfural plant is 3032 tons of furfural per year. The plant location is projected to be in Lomanis, Cilacap, Central Java, with an estimated land area of 3000 m$^2$ or Cikande, Serang, Banten with an estimated land area of 2600 m$^2$. Furthermore, the technical design will be established related to the plant layout with the equipment specifications, production flow, and plant safety analysis. With all information having fulfilled the applicable standards, techno-economic analysis of the plant operations' continuity can be done thoroughly.

3. Results and Discussion
The process runs continuously with an annual operating time of 330 days. The simulation was performed by using SuperPro v9.0 software. Several processes and types of equipment are used to produce furfural and levulinic acid product from the OPEFB, including pre-treatment, size reduction, washing, drying, decanting, evaporation condensation, clarification, hydrolysis, heating or cooling, purification using extraction or distillation.

Pre-treatment aims to maximize the conversion process from OPEFB to the main product. OPEFB size reduction into certain particle size is important to get the maximum particle size in producing furfural and levulinic acid products. The equipment used for size reduction is a shredder and grinder. In this research, the desired particle size is 10 mesh or equal to 2 mm. The first process is shredding the OPEFB into a smaller size. It is then washed using 5 liters of water for 30 minutes to remove ash and other fouling factors and dried under the sun for 10 hours to remove the water.

Pre-treatment using ammonia aims to improve accessibility from OPEFB to produce furfural because ammonia acts as a swelling agent. Thus, the conversion process of cellulose and...
hemicellulose can be increased. Besides, ammonia pre-treatment can produce higher glucose after the enzyme hydrolysis process compared to OPEFB without pre-treatment. Pre-treatment using ammonia was performed by soaking the OPEFB with ammonia 13.13% for 14 hours at room temperature [9]. The decanting, ammonia evaporation and ammonia condensation processes are carried out to recover ammonia. In the ammonia evaporation process, the system is made in isothermal conditions with operating conditions at 40°C and standard pressure using steam as a heating agent for 60 minutes. Thus, ammonia passes through condensation process at 20°C, standard pressure. As a result, there are two outputs: ammonia gas and ammonia solution, which will be recycled.

In this research and simulation, furfural and levulinic acid will be produced from hydrolysis reaction. Furfural will be produced from the hydrolysis reaction of hemicellulose to xylose and later turn into furfural. The levulinic acid will be produced from cellulose hydrolysis reaction into glucose, which then becomes levulinic. The hydrolysis was carried out at 170°C, standard pressure, and using sulfuric acid as a homogenous catalyst. Residence time in the hydrolysis reactor was applied for only 20 minutes.

Condensation, cooling, clarification, and purification process carried out to recover furfural in the liquid form. The condensation process occurs at 150°C, and it is expected that the percentage of the furfural liquid phase obtained is 99%. The cooling process is useful for cooling down a mixture's temperature that contains furfural, HMF, formic acid, and water into 25°C. Therefore, the clarification process aims to separate solid and liquid based on density. The sludge will contain ash, cellulose, hemicellulose, glucose, humins, sulfuric acid, and lignin as a residue. Glucose, levulinic acid, and sulfuric acid will go into distillation for the purification process of levulinic acid. The distillation process's operating condition was carried out at 161°C for the condenser, 240°C for the boiler with reflux ratio 11.8 in the standard column pressure, 80% tray efficiency, and 43 theoretical trays. As a result, levulinic acid purity is 96%.

The other main product is furfural. Furfural purification process is carried out with two variations by using distillation or extraction using a toluene solvent. In the distillation process, the operation condition was carried out at 150°C for condenser and 163°C for reboiler with reflux ratio 2,492, standard pressure, 80% of efficiency tray, and the number of theoretical trays is 61 [4]. From the distillation process, furfural is produced with a 14.97 kg/hour flow rate and a purity level of 99.14%. Toluene is used in the extraction process because it is the best solvent to bind the solute (furfural) [11,12]. The operating conditions were carried out at 25°C, constant pressure, with mixer residence time for 4 hours and settler residence time for 2 hours. Furthermore, to get furfural without toluene, the solvents are separated with thin-film evaporation. The operating condition was carried out at 120°C, standard pressure with a heat transfer efficiency of 90%. Furfural products will come out through the bottom flow with a purity level of 99.95%. The evaporated toluene will come out to be condensed at a temperature of 30°C and a constant pressure.
Table 1. Technical specification of main production equipment

| Equipment       | Mass Rate (kg/h) | Temperature (ºC) | Pressure (kPa) | Volume (m³) | Diameter (m) | Height (m) |
|-----------------|------------------|------------------|----------------|-------------|--------------|------------|
| Shredder        | 2000             | 25               | 101.3          | -           | -            | 21.000     |
| Washer 1        | 910              | 25               | 101.3          | -           | -            | 1.300      |
| Dryer           | 1,938.90         | 70               | 101.3          | -           | -            | -          |
| Grinder         | 1,873.85         | 25               | 101.3          | 14.749      | 1.75         | 9.500      |
| Mixer 1         | 13,116.96        | 25               | 101.3          | 12          | -            | 2.840      |
| Storage Tank    | 13,116.96        | 25               | 152            | 35.259      | 2.464        | 7.394      |
| Decanter 1      | 13,116.96        | 25               | 101.3          | 0.100       | 5.000        | 1.467      |
| Evaporator 1    | 7,450.10         | 40               | 101.3          | 5.985       | -            | 8.000      |
| Condenser 1     | 1,505.45         | 20               | 101.3          | 31.218      | -            | 4.200      |
| Washer 2        | 5,766.86         | 28.60            | 101.3          | 5.2         | -            | 1.300      |

| Equipment       | Mass Rate (kg/h) | Temperature (ºC) | Pressure (kPa) | Volume (m³) | Diameter (m) | Height (m) |
|-----------------|------------------|------------------|----------------|-------------|--------------|------------|
| Mixer 2         | 55,393.34        | 25               | 101.3          | 12          | -            | 2.840      |
| Hydrolysis Reactor | 55,393.34    | 170              | 152            | 20051.570   | 2.170        | 5.424      |
| Condenser 2     | 45,998.50        | 150              | 101.3          | 31.218      | -            | 4.200      |
| Distillation 1  | 245.04           | 105              | 163 (reboiler) | 4.228       | 0.418        | 30.800     |
| Clarifier       | 9394.84          | 25               | 101.3          | 125.147     | 7.29         | 3.000      |
| Distillation 2  | 3435.78          | 161              | 240 (reboiler) | 7.008       | 0.643        | 21.600     |
| Mixer-settler extractor | 490.04       | 25               | 101.3          | 2.118       | 0.45         | 1.800      |
| Evaporator 2    | 265.66           | 120              | 101.3          | 224         | -            | 8.000      |
| Condenser 3     | 250.66           | 30               | 101.3          | 31.218      | -            | 4.200      |

From Table 2, furfural from the distillation process (99.96%) has better purity than extraction process (99.95%). It can happen because the extraction process used toluene as a solvent to bound furfural; therefore, there is some furfural still trapped in the solvent after the evaporation process. Moreover, in the extraction process using mixer-settler extraction, some furfural (2.58%) is wasted into the aqueous phase. Whereas in the distillation process, furfural products are produced using the principle of boiling point differences. The furfural comes out as a bottom product in the distillation process, and water becomes the top product. It can happen because the boiling point water lower than the furfural boiling point. The other product, the levulinic acid in the extraction process and distillation process, has the same purity (99.96%). It can occur because the tools and processes used to produce levulinic acid products are the same; therefore, the product's concentration will also be the same.
This simulation was performed by comparing two different separation methods, distillation and extraction. The economic analysis was conducted by calculating CAPEX and OPEX, for each method of this plant, is shown in Table 3.

Table 3. Economic analysis comparison between extraction and DISTILLATION method

| Component               | Cost ($) |
|-------------------------|----------|
|                         | Distillation | Extraction |
| CAPEX                   |            |            |
| Plant Direct Cost       |            |            |
| Equipment               | 757,000    | 8,330,000  |
| Installation            | 291,000    | 4,012,000  |
| Process Piping          | 265,000    | 2,915,000  |
| Instrumentation         | 303,000    | 3,332,000  |
| Insulation              | 23,000     | 250,000    |
| Electrical              | 76,000     | 833,000    |
| Site and Building       | 341,000    | 3,748,000  |
| Yard Improvement        | 114,000    | 1,249,000  |
| Auxiliary Facilities    | 303,000    | 3,332,000  |
| Indirect Cost           |            |            |
| Engineering             | 618,000    | 7,001,000  |
| Construction            | 865,000    | 9,801,000  |
| Contractor’s Fee        | 198,000    | 2,240,000  |
| Contingency             | 396,000    | 4,480,000  |
| Total Capital Investment| 10,852,000 | 61,805,000 |
| OPEX                    |            |            |
| Raw Material Cost       | 55,718,000 | 73,538,000 |
| Labor Cost              | 1,541,000  | 1,503,000  |
| Facility Cost           | 857,000    | 9,683,000  |
| Laboratory/QC/QA       | 231,000    | 225,000    |
| Waste Treatment         | 3,019,000  | 3,020,000  |
| Utility Cost            | 6,547,000  | 6,677,000  |
| Total Annual Operating Cost | 67,913,000 | 94,646,000 |

From Table 3, the CAPEX and OPEX value for the extraction method is greater than the distillation method. CAPEX value, including the price of equipment, installation cost, and instrumentation of extraction method, is greater than distillation method because the price of the total equipment needed for extraction methods such as extractor and the thin-film evaporator is higher than the price of the distillation column. OPEX of the extraction method is greater because, in the extraction process, it is necessary to purchase additional solvents, which is toluene. In contrast, in the distillation process, no additional materials are needed. CAPEX and OPEX value will then affect the value of ROI, IRR, Payback Time, and NPV. Distillation methods with smaller CAPEX and OPEX have higher ROI and IRR, faster payback time, and greater NPV. These values indicate that the distillation method is more economically beneficial. Profitability analysis comparison between distillation and extraction method is shown in Table 4.

Table 2. Quantity and quality product comparison between extraction and distillation process

|                      | Extraction | Distillation |
|----------------------|------------|--------------|
| Flowrate (kg/h)      | 382.94     | 386.85       |
| Purity (%)           | 99.95      | 99.96        |
| Levulinic acid       | 645.16     | 645.16       |
| Furfural             |            |              |

From Table 2, the quantity and quality product comparison between extraction and distillation process shows that the distillation method has a higher flowrate and purity than the extraction method.
Table 4. Profitability analysis comparison between distillation and extraction method

| Profitability Analysis | Distillation  | Extraction  |
|------------------------|---------------|-------------|
| **CAPEX**              | 10,852,000 $  | 61,805,000  |
| **OPEX**               | 67,913,000 $/yr| 94,646,000  |
| **ROI**                | 31.28 %       | 33.01 %     |
| **IRR**                | 25.86 %       | 26.02 %     |
| **Payback Time**       | 3.20 years    | 3.03 years  |
| **NPV (at 7% interest)**| 15,567,000 $  | 88,023,000  |

After deciding that the distillation method is more economically beneficial, the plant location should be considered. There are two choices of the plant location. Location 1, located in Jl. MT. Haryono, Lomanis, Kab. Cilacap, Jawa Tengah, is nearer to the targeted consumers, which is PT. Pertamina, meanwhile location 2, located in Jl. Modern Industri, Cikande, Serang, Banten, is nearer to the raw material supplier. Profitability analysis comparison between location 1 and location 2 of the plant is shown in Table 5.

The economic analysis between the two locations does not show many different values. The only difference is in the value of OPEX, ROI, and NPV. The OPEX change is due to differences in transport costs per year. This will affect cash flow so that the NPV value at location 1 and location 2 is different. NPV value of location 1 (Cilacap) is greater than location 2 (Banten). Thus, location 1 (Cilacap) is more economically profitable.

Table 5. Profitability analysis comparison between location 1 and location 2

| Profitability Analysis | Location 1 (Cilacap) | Location 2 (Banten) |
|------------------------|-----------------------|---------------------|
| **CAPEX**              | 62,651,000 $         | 62,707,000 $       |
| **OPEX**               | 94,245,000 $/yr      | 94,715,000 $/yr    |
| **ROI**                | 33.09 %               | 32.61 %             |
| **IRR**                | 26.17 %               | 25.70 %             |
| **Payback Time**       | 3.02 years            | 3.07 years          |
| **NPV (at 7% interest)**| 89,739,000 $         | 87,430,000 $       |

Figure 3. Plant Location in Cilacap (left) and Banten (right)
4. Conclusion
The furfural purification method with extraction is more effective and beneficial based on the purity of furfural produced and economic analysis. Another variation is added in the extraction method, plant location, which is close to the raw material (OPEFB) and close to the distribution center. The OPEFB-based furfural purification plant with the distillation method can produce furfural with a purity of 99.95%. The value of IRR and ROI from the calculation is 26.02% and 33.01%. The NPV of this plant is 88,023,000 USD. It can be concluded from the profitability analysis that this plant located in Cilacap with a capacity of 3032 tons of furfural per year is economically feasible with a payback period of 3.02 years.

5. References
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