Techno-economic assessment of Levulinic Acid Plant from Sorghum Bicolor in Indonesia

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Abstract. The increasing need of energy is one of the main energy security issues in Indonesia. Hence, alternative energy is needed. Levulinic acid (LA) is among chemical platform used in the synthesis for a variety of high-value materials, such as fuels and commodity chemicals. It is predicted that global LA market demand to reach 3.1 tons in 2016. This study examines industrial process design and economic analysis for LA production in Indonesia. Sorghum bicolor was used as feed because of its high cellulose, low lignin contents and availability in Indonesia. The conventional economic problem from biomass based production was diminished since the valuable waste from pretreatment process was sold to other industry. This plant was recommended to be built in an industrial estate area in Jawa Timur (East Java) province. Results from simulation using SuperPro Designer 9.0 was used for the techno-economic assessment. The plant assessment showed that the minimum production capacity was 7.7 ton per day to achieve an internal rate of return (IRR) and payback period (PBP) values of 19.61% and 3.93 years, respectively. Sensitivity analysis showed that product selling price was the most predominant factor for IRR, NPV, PBP and ROI. Raw material and water had low effects on those economic parameters. These values indicated that LA plant was feasible to be built in Indonesia.

1. Introduction

Currently, humankind has three major energy security problems, i.e. the increasing of fossil energy consumption, the fossil fuel depletion time and the environmental degradation caused by fossil fuel consumption. These problems are closely related to each other and create a huge challenge for the development of alternative energy source [1].

Earth has an abundant supply of biomass, especially those which located in the forest and vast ocean. The biomass availability potential in Indonesia is predicted 32,654 MW [2] or around 0.62 \(10^{18}\) J/year with load factor 0.6. The world has total biomass availability around 200 \(10^{18}\) J/year [3]. Mostly, biomass is used to feed the living creatures, especially human, but it also has another function as an energy source. In the past decade, the researchers and industry have focused on the biomass conversion to energy source [4,5]. Accordingly, biomass utilization as an alternative energy source would provide a great benefit to overcome the aforementioned problems.
In Indonesia, the increase of energy consumption is 8% per year. This value was predicted to increase together with the growth of the economy and human population [6]. Biodiesel is one of the proven alternative energy which can be used in Indonesia. The production of biodiesel in Indonesia is 2 million kL/year and it is predicted to reach five million kL/year [7]. In recent years, researcher has considered LA as one of the most promising chemical platforms for producing fuel such as biodiesel [8]. Besides biodiesel, LA, or sometimes called as 4-oxopentaoic acid, also has an important role as building compound to produce another compounds, such as 5-bromolevulinic acid, valeric acid, methyltetrahydrofuran (MTHF), methyl pirolidon and many more [9,10]. Up to now, several LA plants from biomass are successfully operating around the world and more projects are underway (see Table 1).

| Company           | Information                                                                 | Reference |
|-------------------|-----------------------------------------------------------------------------|-----------|
| Biofine           | In 1994, constructed one ton/day demonstration plant in South Glens Falls, New York (operated for 10 years) | [11]      |
| Segetis           | In 2013, started pilot plant in Golden Valley, Minnesota                     | [12]      |
| GFBiochemicals    | In 2015, started 10,000 MT/year commercial plant in Caserta, Italy (planned to scale-up to 8,000 MT per year by 2017) | [13]      |

Until this work was finalized there is no Levulinic Acid (LA) plant in Indonesia. However, there is growing global market of LA over the last decades. With a global high prices from 5 to 8 $/kg [14] it is an attractive renewable platform especially for the main consumers such as the agricultural, pharmaceutical, cosmetic and food industry. Even though, having a ketone and carboxylic group, it has high functionality for a wide range of applications like polymers, plasticizers or fuel additives[15]. Some companies such as Biofine, Segetis and GFBiochemicals, are planning to expand the global market of LA as seen in Table 1.

Production of LA and biodiesel as LA derivate may contribute to reducing Indonesian oil import. The development of LA industry was slow in 1990’s because the synthetic raw material was expensive and the yield obtained from the process was small. To overcome this condition, biomass is used to replace the synthetic raw material to produce LA. Cellulose, which is contained in the biomass, can be used as main raw material. Sweet sorghum (Sorghum bicolor) is one of the biomass which can be used to produce LA. Sorghum is one kind of biomass which is originated from tropic and subtropic area in Southeast Pacific and Australasia regions (Australia, New Zealand, and Indonesia). The availability of S. bicolor is abundant in Indonesia. The cellulose composition in this species is relatively high, 31.42%, which make this species suitable to be used in LA production.

Looking at the importance of alternative energy and the availability of Sorghum bicolor in Indonesia, the establishment of LA plant from Sorghum bicolor seems to be beneficial. Since there is no LA plant in Indonesia before, a sophisticated process design is needed in which the process must be socially acceptable and economically feasible. The techno-economic assessment can be used as a tool to evaluate the uncertainty from the technologic and economic point of view. This assessment is a valuable asset to help the Indonesian policy makers and investors to make their decision.

Production unit design is one of the most important things to do before building a plant. There are several factors to be considered in designing the unit processes, such as the selection of the simulator. The selected simulator should be able to perform rigorous mass and energy balance calculations of the overall process. It also needs to perform economic analysis automatically by maintaining some variables which already contained in the simulator option. The simulation result
is used to determine the feasibility of the plant. SuperPro Designer 9.0 is a simulator that can fulfill those criteria. The strength of this application, such as material balance calculation of the overall process, equipment sizing, product analysis, and economic analysis made this application chosen as the simulator in this study.

This study conducted assessment of the economic viability in LA production based on *Sorghum bicolor* in Indonesia through the economic calculation using SuperPro Designer 9.0. The variation in production capacities which simulated in SuperPro Designer 9.0 is reviewed in economic evaluation. The IRR, NPV, and PBP showed the feasibility of LA plant to be built in Indonesia. The sensitivity analysis was also performed to obtain the correlation between raw material cost, water, and selling price.

2. Material and method

2.1. Raw material

In this work, sorghum was chosen as raw material because of its suitable properties. The low amount of lignin contained in the raw material (7.57%) can make the pretreatment process more effective, and the high amount of cellulose can increase the yield of LA product during the hydrolysis process [16].

Indonesia is the ninth biggest sorghum producer after India, China, Nigeria, United States, Sudan, Argentina, Mexico, and Thailand [17]. In Indonesia, sorghum has been recognized widely, especially in Jawa, NTB, and NTT. Sorghum has many strong points, i.e. resistant to drought, high production, inexpensive production costs, and resistant to pests as well as diseases. This condition makes sorghum become one of the feasible biomass, which can be developed in Indonesia [18].

Simulation

In this work, SuperPro Designer 9.0 (then is called SuperPro) was used to design, simulate and optimize the LA production process. Firstly, Block Flow Diagram (BFD), as in Figure 2, was used to develop arrangement of unit procedures in SuperPro. Then, data from previous researches as well as literature were collected to provide operating conditions data required by the SuperPro. Economic calculations were done by SuperPro and became the basis data for setting up for production capacity.

The raw material input acts as the independent variable while the value of IRR, PBP, ROI, NPV, and sensitivity analysis result act as the dependent variable. Through this work, the selected production capacity was expected to achieve the IRR and PBP value of more than 14% and less than five years respectively. This value refers to the MARR value for chemical industry and plant-overall lifetime, which is expected to be 15 years [19].

Prior to the whole plant simulation, preliminary economic analysis was performed. Assessment was done by simulating only the unit in charge of hydrolysis lignocellululose and converting it to levulinic acid. Conversion of lignocellulosic material to LA can be performed by acid hydrolysis. Equipment cost data used was taken from SuperPro built in cost model.

2.2. Process description and simulation

Biorefinery concept can be applied in this plant because multi products can be produce such as LA, formic acid, and furfural from *Sorghum bicolor*. LA is the main product, while formic acid and furfural are the side products. Biorefinery is a system that processed or fractionated bio-based source to obtain more than one product including bioenergy, biofuels, chemicals and high value-added compounds [20].

*Sorghum bicolor* grains were ground and given a pretreatment with dewaxing (extraction) and delignification (filtering) processes. Hydrolysis process was then carried out using homogeneous catalyst followed by neutralization. Cellulose and hemicellulose were two out of three components obtained form lignocellulosic material. These components are polymer that can be attacked through hydrolysis. The hydrolysis product of cellulose is glucose (C$_6$). Meanwhile, the product of
hemicellulose is xylose (C₅). Decomposition of C₆ with acid as catalyst produced 5-hydroxymethyl-2-furaldehyde as an intermediate product. Further rehydration gave LA and formic acid. Decomposition of C₅ gave furfural. Clarification was done to separate the remnants of lignocellulose which were not hydrolyzed. At the end of the process, multiple distillation was carried out to separate the formic acid, furfural and LA. The whole process was simulated under continuous operation mode. The process block flow diagram generated is shown in Figure 1.

Figure 1. Block flow diagram of levulinic acid production.

Figure 2. Simulation flowsheet of levulinic acid production.
Figure 2 shows the simulation of LA production process using SuperPro Designer 9.0. In this simulation, data of operating condition for each unit operation were obtained from open literature and industry. The data include input and output stream composition, preparation condition of each production unit, and constraint in each operating unit. The selected criteria and operating condition are shown in Table 2.

**Table 2.** Selected criteria and operating condition of LA process.

| Process             | Equipment Code | Criteria and Operating Condition                                      | Reference |
|---------------------|----------------|-----------------------------------------------------------------------|-----------|
| Size Reduction      | GR-101         | Equipment: Disk Mill, Power: 1.1 kW, Output: 315 microns              | [21]      |
| Solid-Liquid Extraction (Dewaxing) | SMSX-101   | Temperature: 80°C, Residence Time: 6.5 hours, Solvent: Hexane & ethanol mixture (2:1) | Preliminary work |
| Delignification     | MX-101         | Solvent: NaOH, Concentration: 10%, Temperature: 72.5°C, Impeller Speed: 190 rpm | [13], [22], [23] |
|                      |                | % Component Removal: Cellulose: 20%, Hemicellulose: 41.4%, Lignin: 70% | Preliminary work |
| Hydrolysis          | R-101          | Catalyst: H₂SO₄, Concentration: 1%, Residence Time: 20-25 minutes, Temperature: 130°C, Impeller Speed: 100 rpm | [9,10], [10], [23] |
| Purification        | C-101/102/103  | Separation: 3 stage Distillation, Lignocellulose relative volatility | Preliminary work |

Some researchers have studied the utilisation of acidic [24,25] and base pretreatments. Base pretreatment has shorter residence time (1-2 hours) compare to acidic (20-30 hours). Base pretreatment works at lower temperature (50 °C) than acidic pretreatment (120-150°C). Although we have to use higher concentration of base, the price of base is much lower. Other benefit of using base pretreatment is its broader lignin tolerance. Having these advantages, we selected base pretreatment.

For hydrolysis reaction, there are some available options [10, 26, 27], which basically fall into homogenous (H₂SO₄, HCl) and heterogenous catalyst (Mn/ZSM-5). Homogenous catalyst was selected due to its higher conversion, selectivity and LA yield. It also has lower price and modest temperature (120°-150°C). The disadvantages is its higher corrosivity. However, selection of vessel materials and concentration of acid might reduce this problem. In the hydrolysis reactor there are multiple reactions following this model,

$$k = (C_{H^+})^a \cdot k_0 \cdot \exp\left(-\frac{E}{RT}\right)$$ (1)
The kinetic and Arhenius parameters of those reactions are illustrated in Figure 3.

![Chemical reactions diagram]

**Figure 3.** Kinetic parameters for hydrolysis reactions in production of Levulinic Acid and Formic Acid from cellulose, modified from [28].

### 3. Results and discussion

#### 3.1. Plant location

Plant location selection is one of the main factors in determining the success of a plant. Therefore, some important factors such as raw materials availability, utilities, market, communication access, and transportation should be considered properly. Central Java and East Java are the two provinces with the largest sorghum producer. To determine the location of the plant, a review of some aspects of these two provinces was conducted as shown in the Table 3.

| Criteria                              | Central Java | East Java |
|---------------------------------------|--------------|-----------|
| The distance of proposed plant location to the nearest market target | (Reference city: Semarang) | (Reference city: Surabaya) |
| - Tuban (km)                          | 210.4        | 103.0     |
| - Cilacap (km)                        | 260.5        | 504.1     |
| - Gresik (km)                         | 293.8        | 21.6      |
| Total distance (km)                   | 764.7        | 628.7     |
| Raw Materials Availability (ton/years) | 57,000       | 55,000    |
| Raw Materials Production Area (ha)    | 19,000       | 10,000    |
| Raw Materials Productivity (ton/ha)   | 3            | 5.5       |
| The Largest Industrial Area (ha)      | 450          | 835       |

East Java is closer to the main market targets of levulinic acid, i.e. Tuban, Cilacap, and Gresik. The shorter distance to the target market renders lower distribution costs. East Java also possesses bigger industrial area, such as Gresik Industrial Estate (140 ha), Ngoro Industrial Park Mojokerto (440 Ha), and Surabaya Industrial Estate Rungkut (835 Ha) [29]. Sorghum production in East Java
is slightly lower than that in Central Java. However, there is a much progressive productivity and an ambitious plan in East Java to expand the plantation area. Therefore, East Java is selected as the location of the LA plant.

Surabaya Industrial Estate Rungkut (SIER), located in East Java, is an industrial area that was designed with the concept of an integrated industrial area, flood-free, and ready to use with the empty area offered is 401 hectares [29]. SIER also offers advantages in term of transportation. It has relatively short distance to the seaport, airport, rail station and highway gate as depicted in Table 4.

| Table 4. Average mileage of SIER to transportation gate [30] |
|-------------------------------------------------------------|
| Destination                | Distance (km) |
| Juanda International Airport  | 5             |
| Tanjung Perak Seaport       | 19            |
| Gubeng Rail Station        | 10            |
| Surabaya-Gempol Highway Gate | 5             |
| Central Government Area of Surabaya | 8            |

3.2. Production capacity determination
Various raw material input range from 30 to 55 tonnes per day, were simulated in SuperPro influenced the values of IRR and PBP as shown in Table 5. Input of 30 tonnes per day, which produces 5.78 tonnes LA per day, results in high unit production cost for all the products (Levulinic acid, Furfural, Formic Acid and Lignin waste) which is 11.15$/kg. The SuperPro calculates Unit Production Revenue based on total revenue divided by the main stream product which was set in our simulation as LA stream. The simulation data of all products were set based on on market price, i.e. 7.62 $/kg LA; 1.2 $/kg Furfural; 0.95 $/kg Formic acid; and 0.09 $/kg Lignin waste. The calculated unit production revenue is 9.89 $/kg. Thus, the IRR and PBP were not available (N/A). Higher raw material input makes the increase in IRR and reduction of PBP.

| Table 5. Variation of production capacity to IRR and PBP. |
|-----------------------------------------------------------|
| Raw Material Input (tons of *S. bicolor*/day) | Production Capacity (tons of LA/day) | Production Cost ($/kg main product) | IRR (%) | PBP (year) |
| 30 | 5.78 | 11.15 | N/A | N/A |
| 35 | 6.75 | 9.72 | 3.52 | 9.96 |
| 40 | 7.75 | 8.66 | 19.61 | 3.93 |
| 45 | 8.68 | 7.82 | 31.95 | 2.45 |
| 50 | 10.15 | 6.64 | 49.14 | 1.52 |
| 55 | 10.61 | 6.60 | 52.27 | 1.41 |

Figure 4 shows the relationship between production capacity and the IRR as well as PBP. In this work the cross point, i.e. 40 tons raw material input per day, has IRR 19.61% and PBP 3.93 years. These fulfill the requirement of IRR >14% and PBP <5 years for an interesting investment. Further calculation on this work is then based on this *Sorghum bicolor* material input.
3.3. Economic analysis

Total capital investment consists of equipment purchase cost, bulk material cost, and other costs that can be seen from the table below:

| Component                        | Cost (US$) |
|----------------------------------|------------|
| **Total Plant Direct Cost (TPDC) (Physical Cost)** |            |
| 1. Equipment Purchase Cost       | 1,326,000  |
| 2. Equipment Installation        | 340,000    |
| 3. Process Piping                | 464,000    |
| 4. Instrumentation               | 530,000    |
| 5. Insulation                    | 40,000     |
| 6. Electricity Installation      | 133,000    |
| 7. Building                      | 597,000    |
| 8. Yard Improvement              | 199,000    |
| 9. Auxiliary Facilities          | 530,000    |
| TPDC                             | 4,158,000  |
| **Total Plant Indirect Cost (TPIC)** |          |
| 11. Engineering                  | 1,039,000  |
| 12. Construction                 | 1,455,000  |
| TPIC                             | 2,495,000  |
| **Total Plant Cost (TPC = TPDC+TPIC)** |          |
| TPC                              | 6,653,000  |
| **Contractor’s Fee & Contingency (CFC)** |  |  
| 13. Contractor’s Fee             | 333,000    |
| 14. Contingency                  | 665,000    |
| CFC                              | 998,000    |
| **Direct Fixed Capital Cost (DFC = TPC+CFC)** |          |
| DFC                              | 7,650,000  |
| **Working Capital (WC)**         |            |
| WC                               | 1,679,000  |
| **Total Capital Investment (TCI)** |          |
| TCI                              | 9,329,000  |

**Figure 4.** Production capacity versus IRR and PBP of LA production.
Table 7. Total operational cost of LA plant

|                      | Cost  | %    |
|----------------------|-------|------|
| Raw Material         | 9,696,000 | 48.53 |
| Direct Labor Cost    | 434,000  | 2.17  |
| Facility-Dependent   | 1,445,000 | 7.23  |
| Laboratory/QC/QA     | 65,000   | 0.33  |
| Waste Treatment      | 99,000   | 0.49  |
| Utility              | 8,241,000 | 41.24 |
| TOTAL                | 19,981,000 | 100     |

The raw material and utility costs were the most important component in total operating cost. The main contributors for the high raw material cost were the high amount of raw materials used in this plant. These include solvent (n-hexane and ethanol), catalyst (sulfuric acid), and *Sorghum bicolor* itself. Besides, the high amount of energy required renders high utility cost percentage in this biorefinery plant.

Table 8. Profitability analysis of LA plant.

| Production Capacity |                |
|---------------------|----------------|
| Lignin Waste        | 11,501 ton/yr  |
| Formic Acid         | 2,065 ton/yr   |
| Furfural            | 413 ton/yr     |
| Levulinic Acid      | 2,546 ton/yr   |

| Revenue             |                |
|---------------------|----------------|
| Lignin Waste        | $90/ton        |
| Formic Acid         | $950/ton       |
| Furfural            | $1,200/ton     |
| Levulinic Acid      | $7,620/ton     |

Profitability Analysis

| Good Margin         | 12.71%         |
| Return On Investment| 25.46%         |
| Internal Rate of Return | 19.61% |
| Net Present Value   | $8,653,000     |
| Payback Period      | 3.93 Years     |

Profitability analysis in LA plant has been calculated automatically by SuperPro Designer 9.0. The result is shown in Table 9. LA was not the only product obtained from the plant. The existence of furfural and formic acid as byproducts also increased the revenue. LA industrial price was within the range of US$ 5 to 8 per kilogram, while furfural and formic acid industrial price was assumed US$ 1.2 and S$ 0.95 per kilogram respectively[14]. LA price used in this plant was US$ 7.6. To increase the plant revenue, the processable waste was also sold, such as NaOH and lignin mixture which obtained from delignification process. If we observed the plant based on its function, NaOH and lignin mixture was not used anymore. Lignin and NaOH purification process will only increase plant production cost. Because of these reasons, lignin and NaOH mixture were sold to the industry which undergo lignin purification. Based on the product selling price, total plant revenue was US$ 22,732,927. This revenue made the ROI, IRR, and PBP value of 25.46%; 19.61%; and 3.93 years,
respectively. The value of IRR and PBP that was less than one-third of plant lifetime will attract investor to invest in this plant.

### Table 9. Technology comparation.

| Product          | Biofine [11] | Biofuel [31] | Biorefining [31] | Our study |
|------------------|--------------|--------------|------------------|-----------|
| Levulinic acid   | 0.157        | NA           | 0.252            | 0.194     |
| Furfural         | 0.076        | 0.107        | 0.157            | 0.031     |
| Formic acid      | 0.062        | 0.100        | 0.100            | 0.002     |
| Lignin           | NA           | 0.180        | 0.180            | 0.154     |
| EtillLevulinat   | NA           | 0.313        | NA               | NA        |
| AHRs             | 0.517        | 0.151        | 0.151            | NA        |

The content of LA generated in this work lies between Biofine and Biorefining. The different is not only due to raw material but also the kinetic and other parameters.

3.4. Sensitivity analysis

Sensitivity analysis was performed to determine a correlation between direct-indirect cost and every component in profitability analysis, such as IRR, NPV, ROI, and PBP (Figure 5-8). In this plant, raw material cost, utility cost (water) and product selling price was chosen as the parameter in this sensitivity analysis.

![Figure 5. NPV sensitivity analysis.](image)
**Figure 6.** IRR sensitivity analysis.

**Figure 7.** PBP Sensitivity Analysis
NPV and IRR value rose up with the increasing of LA price as expected. The higher the LA price, the bigger the company profit. With the increasing of the LA price, the PBP also becomes shorter. The parameter which affects IRR, NPV, ROI, and PBP the most was product selling price itself. On the other hand, raw material cost was not significantly affects IRR, NPV, ROI, and PBP. Deviation of utility cost did not have significant effect on the change of NPV, IRR, PBP, and ROI. This can be seen from the stagnant graph on NPV, IRR, ROI, and PBP when utility cost increased and lowered. This may happen because those parameters only took a small portion of the total operating cost.

4. Conclusion
In this work, LA production from *Sorghum bicolor* consisted of three main processes: pretreatment, hydrolysis, and separation process. Optimization by using SuperPro Designer 9.0 showed that the minimum production capacity was 7.71 tons of LA per day resulted from 40 tonnes *Sorghum bicolor* per day as raw materials. This meant that the LA yield was 19.4% (ton of LA resulted per ton of Sorghum bicolor in input). Besides LA, side products as furfural, and formic acid were also formed 3.1% and 0.2%, respectively. This integrated LA plant design achieved the value of IRR 19.61% and 3.93 years of PBP.

**Abbreviation**

- CFC: Contractor’s Fee & Contingency
- DFC: Direct Fixed Capital Cost
- IRR: Internal Rate of Return
- LA: Levulinic Acid
- MARR: Minimum Acceptable Rate Of Return
- NPV: Net Present Value
- PBP: Payback Period
- POEFB: Palm Oil Empty Fruit Bunches
ROI  Return On Investment
TCI  Total Capital Investment
TPC  Total Plant Cost
TPDC  Total Plant Direct Cost
TPIC  Total Plant Indirect Cost
WC  Working Capital

Acknowledgment
The authors acknowledge financial support from Indonesia Estate Crop Fund for Palm Oil (BPDPS Research grant number Peng-01/DPKS.4/2015). Preliminary part of this research was funded by The Ministry of National Education, Republic of Indonesia through Competitive Research Grant number 2245/H2.R/12/HKP.0500/2014. The authors also gratefully acknowledge Center of Bioindustrial Technology, Agency for Assessment and Application of Technology (BPPT), The Ministry of Research and Technology, Republic of Indonesia for the technical supports.

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