Integrated Biorefinery Technology: Monetization of Oil Palm Empty Fruit Bunch to Biofuel & Bio-based Chemicals, and Beyond

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Abstract. As the largest producer of palm oil, Indonesia has abundant oil palm empty fruit bunch (EFB), as one of the solid wastes produced from palm oil mill, which utilization has not yet been optimal although it has a potency to be used as feedstock for biofuel and bio-based chemicals. However, due to the recalcitrant characteristic of EFB as lignocellulosic material, EFB conversion into biofuel and bio-based chemicals has been a challenge, especially in regard to its economic viability. To obtain the economically viable of the conversion of EFB, the integrated EFB biorefinery technology concept was proposed to produce multiple products which are precursors for biofuel and bio-based chemicals. This paper presents the integrated EFB biorefinery technology concept, economic analysis of the technology, the role of the technology for circular bioeconomy in Indonesia, and the biorefinery industrialization concept in Indonesia as part of an effort for “Making Indonesia 4.0”.

1. Introduction

Indonesia has the largest palm oil plantation in the world with palm oil production reaching 43 million tonnes in 2019 [1]. Oil Palm Empty Fruit Bunch (EFB) is the largest solid waste generated from palm oil mills, and as much as 1.1 tonnes of EFB is generated for every tonne of palm oil produced [2]. The production of palm oil is expected to increase. Based on extrapolation using data obtained from the Ministry of Agriculture [1], EFB production is projected to reach 94 million tonnes by 2030.

As lignocellulose, EFB mainly consists of cellulose, hemicellulose and lignin, which can be used for the production of biofuel and a vast array of bio-based chemicals, such as butanediol, ethanol, ethylene, acetic acid, xylitol, levulinic acid, BTX (benzene, toluene, xylene) [3]. Due to its abundance, low price, and its great utilization potential, EFB is considered as one of the most promising biomasses for biorefinery feedstocks, particularly in Indonesia.

Various research related to EFB conversion into bio-based chemicals have been reported [4–17]. However, none of the research is developed until the commercialization stage. There are some constraints encountered during the implementation of this technology, such as: (1) low density of EFB
which results in the high transportation and storage cost; (2) current utilization of EFB as mulch or compost feedstock which may affect the EFB supply for biorefinery; and (3) technical barriers which affect the economic viability of the technology, such as the inconsistency of biomass composition which affects the product yield, low concentration of sugar in the hydrolysate, high consumption of enzyme/chemicals accompanied by their high cost, and difficulties in high solid loading operations [18]. Some methods have been reported to overcome these problems, such as the installation of feed handling facility in the palm oil mills to increase the density of EFB prior to transporting [18], the use of solid residue-by-products obtained from biorefinery as a fertilizer to replace mulch [18], fed-batch operation [7], enzyme recycling [19], and membrane separation [20] to increase the product yields and to reduce the enzyme/chemical consumptions.

In Indonesia, many studies regarding the conversion of EFB into biofuel and bio-based chemicals have been carried out. Most researchers, however, focus on single constituent of EFB while neglecting the others despite their potential utilization [4–15, 21–24]. Only few studies reported the optimization of the utilization of more than one component of EFB as in biorefinery [25]. The concept of biorefinery is one of the solutions to increase the economic viability of EFB monetization as well as to maintain the sustainability of the process and helps to move towards a circular bioeconomy [26–28]. A biorefinery technology is needed as a bridge which connects all EFB-based research and promotes in accelerating the development of biofuel and bio-based chemicals production technology, particularly in Indonesia.

PT Rekayasa Industri and researchers from Institut Teknologi Bandung, have succeeded in developing the technology for processing EFB into glucose on a lab scale with satisfactory results, where the consumption of chemicals and enzyme was minimized, while maintaining high product yields and concentration which is described in our patent pending (Indonesia Patent No.P00201803638; International PCT patent No.PCT/IB 2019/054125). Currently, in collaboration with researchers from Institut Teknologi Bandung and Centre for Agro Based Industry-Ministry of Industry, we are developing EFB biorefinery technology on a pilot scale which is funded by The Indonesian Palm Oil Plantation Fund Management Agency.

This paper presents the integrated EFB biorefinery technology concept, economic analysis of the technology, the role of the technology for circular bioeconomy in Indonesia, and its position in the industrialization concept as part of an effort for "Making Indonesia 4.0".

2. Methodology

2.1. Process modelling
The process model used to simulate the biorefinery technology to convert EFB into glucose, xylose and lignin is based on our patent pending, publications and non-confidential inputs from Institut Teknologi Bandung as our research partner. The techno-economic calculation model is prepared in Excel Spreadsheet. The design basis for pretreatment and hydrolysis reaction models for glucose production are obtained based on our patent pending (Indonesia Patent No.P00201803638; International PCT patent No.PCT/IB 2019/054125), while pretreatment and hydrolysis reaction models for xylose production as well as pretreatment reaction model for lignin production are prepared based on data from Institut Teknologi Bandung as our collaborator [11]. The heat exchange and evaporation processes were simulated using Aspen HYSYS software.

The composition of cellulose, hemicellulose and lignin, the main constituent of EFB, varies depending on plant’s age, growth condition, the climate and soil conditions [29, 30]. Table 1 shows the composition of the EFB used in this study.
### Table 1. Composition of EFB in dry basis (%-wt).

| Component        | %-wt |
|------------------|------|
| Cellulose        | 34   |
| Hemicellulose    | 31   |
| Lignin           | 22   |
| Others           | 13   |

2.2. **Total Capital Investment calculation method**

Equipment sizing was done manually based on capacity. The purchase price of equipment is estimated by means of scaling-down or scaling-up from a literature data such as National Renewable Energy Laboratory (NREL) Report [33] or our database of a known size as depicted in Eqn (1):

\[
P_{\text{purchase}} = P_{\text{purchase of a known size}} \times \left( \frac{\text{size}}{\text{known size}} \right)^n
\]

Where \( n \) is the power coefficient with a value of 0.5–0.8, depending on the type of equipment. The factors used to estimate other direct cost and indirect cost to calculate total capital investment cost are obtained from NREL Report [33].

2.3. **Unit cost of main raw materials and utilities**

Table 2 shows the unit cost of main raw materials and utilities used to calculate operating cost and economic analysis. The costs are obtained from our database and National Renewable Energy Laboratory (NREL) Report [33], and has been corrected using inflation rate.

### Table 2. The unit cost of main raw materials and utilities.

| Materials                                         | Price     |
|---------------------------------------------------|-----------|
| Butanol                                           | $1,000.00 ton\(^{-1}\) |
| Chemical Cooling Tower                            | $2,716.00 ton\(^{-1}\) |
| Chemical for Waste Water Treatment                | $410.00 ton\(^{-1}\) |
| Cooling Water                                     | $0.14 ton\(^{-1}\) |
| Electricity                                       | $0.08 kWh\(^{-1}\) |
| Cellulase Enzyme                                  | $4,000.00 ton\(^{-1}\) |
| Oil Palm Empty Fruit Bunch                        | $6.90 ton\(^{-1}\) |
| Process Water                                     | $0.55 ton\(^{-1}\) |
| Steam                                             | $1.53 ton\(^{-1}\) |
| Xylanase Enzyme                                   | $4,000.00 ton\(^{-1}\) |

2.4. **Other assumptions**

Table 3 summarizes other main assumptions used to calculate the economic analysis. The plant operates for 20 years. The depreciation used is straight line depreciation. The income tax rate is 25%. The inflation rate is 6%. The construction was carried out for 2 years. In the first year of construction, the costs incurred for construction are as much as 40% of the total investment cost, while the remaining costs are used in the second year. In the first year of the operation, only 80% of maximum working capacity is used.
Table 3. Economic analysis assumptions.

| Economic analysis assumptions                        | Value  |
|------------------------------------------------------|--------|
| Plant lifetime (years)                               | 20     |
| Operating hours per year                             | 7920   |
| Equity                                               | 100%   |
| General plant depreciation                           | Straight line depreciation |
| Depreciation period (years)                           | 10     |
| Construction period (years)                          | 2      |
| % spent in year -1                                    | 40%    |
| % spent in year 0                                     | 60%    |
| Revenues in year 1                                    | 80%    |
| Revenues in year 2                                    | 100%   |
| Income tax rate                                      | 25%    |
| Working Capital                                      | 5% of TCI |

3. Result & Discussion

3.1. The integrated EFB biorefinery technology concept: EFB Fractionation

The concept of the integrated EFB biorefinery technology is to fractionate the three main constituents of EFB and convert them into glucose, xylose, and lignin through sequential processes as described in Figure 1. The processes are divided into three main stages, namely: (1) Xylose production: Hemicellulose fractionation through hydrothermal pretreatment followed by an enzymatic hydrolysis reaction to convert hemicellulose to xylose, (2) Lignin production: lignin fractionation through organosolv pretreatment, and (3) Glucose production: cellulose fractionation using steam explosion pretreatment followed by an enzymatic hydrolysis reaction to convert cellulose to glucose. The process sequence is determined based on the consideration that hemicellulose is the most easily degraded part among all EFB constituents, thus requires the mildest operating condition for recovery [15, 31]. Hydrothermal was considered as the most suitable technique for hemicellulose recovery due to its ability to selectively remove hemicellulose while leaving the other constituents as essentially intact [31, 32].

![EFB fractionation process scheme](image)

**Figure 1.** EFB fractionation process scheme.

3.1.1. Xylose production. Shredded EFB is pretreated hydrothermally in R-101 at temperature 140 - 200°C under saturated pressure. The reaction was held for 20 - 40 minutes. Both the pretreated solid and
The liquid are sent to hydrolysis reactor R-102. The hydrolysis reaction is carried out at 50°C and pH 5.0 for 24 - 48 hours using commercial xylanase. The broth is separated from the pretreated solid prior to purification. Purification process is conducted using evaporator E-101 to produce concentrated xylose (60%-wt).

### 3.1.2. Lignin recovery

The remaining solids from R-102 are pretreated using organosolv method in R-201 at temperature 140 – 200°C under saturated pressure. A mixture of butanol and water is used as the solvent. The reaction was held for 20 - 40 minutes. The broth is separated from the remaining solid prior to purification. Purification process is conducted using evaporator E-201 to produce concentrated lignin (60%-wt).

### 3.1.3. Glucose production

The remaining solid from R-201 is pretreated using steam explosion method in R-301 at temperature 140 – 200°C under saturated pressure. The reaction was held for 10 - 20 minutes. The liquid is recovered prior to be sent to hydrolysis reactor R-302. The hydrolysis reaction is carried out at 50°C and pH 5.0 for 24 - 48 hours using commercial cellulase. The broth is then purified in evaporator E-301 to produce concentrated glucose (60%-wt).

The yields for concentrated xylose, concentrated lignin and concentrated glucose are 0.8, 0.46, and 0.38 ton/ton dry EFB, respectively.

### 3.2. Economic analysis

The EFB biorefinery capacity used in this study is 60 k-ton EFB wet basis per annum. This capacity selection is based on the average EFB production rate from one palm oil mill with the capacity of 240 k-ton fresh fruit bunch per annum. This is in accordance with the concept of “one palm oil mill, one EFB biorefinery plant”, which helps in reducing the cost for transportation as well as minimizing the need for storage. EFB produced from palm oil mill is washed and dried before being shredded.

Table 4 shows the detail of total investment cost. The total capital investment cost for EFB biorefinery with capacity of 60 k-ton EFB wet-basis per annum is 40.98 million USD.

| Table 4. Total capital investment cost breakdown. |
|-----------------------------------------------|
| Direct costs                                  |
| Total installed equipment cost                | 1.00   | 29.27 million USD |
| Other direct costs                           |
| Warehouse                                     | 0.04   | 1.17 million USD  |
| Site development                              | 0.04   | 1.17 million USD  |
| Additional piping                             | 0.04   | 1.17 million USD  |
| Total direct costs                           | **1.12** | **32.78 million USD** |
| Indirect costs                               |
| Field Expense                                 | 0.056  | 1.64 million USD  |
| Home Office and Construction Fee              | 0.056  | 1.64 million USD  |
| Project Contingency                           | 0.056  | 1.64 million USD  |
| Other Cost (start up, permits, insurance, etc)| 0.112  | 3.28 million USD  |
| Total Capital Investment (TCI)                | **1.40** | **40.98 million USD** |

Figure 2 shows the share of each components constituting direct cost of the total capital investment in a pie chart. Xylose production area accounts for the largest portion of the direct cost, 38%, as the equipment capacity in this area is bigger than in other areas. Despite its bigger capacity as the second process area, the lignin production area accounts for roughly the same cost, 21%, as the glucose production area, 19%. This is because lignin production area comprises only pretreatment reactor, filter and evaporator as its main equipment, while glucose production area includes hydrolysis reactor.
Figure 3 shows the share of components constituting the operating cost in a pie diagram. Butanol contributes the largest portion of the operating cost, which is about 52%, followed by enzyme 20% and utilities 11%. The high consumption of solvent due to moderate solid loading operation (S/L 15–25%) in organosolv pretreatment as well as the high price are the main reasons for the major contribution of butanol. On the other hand, despite its high price, the moderate contribution of enzyme is attributed to the high solid loading operation (S/L 25–35%) in hydrolysis.

Table 5 summarizes the results of the economic analysis. The economic analysis was calculated at selling price of concentrated xylose, concentrated lignin and concentrated glucose 308.70, 594.01[34] and 113.00 USD/ton, respectively. The internal rate of return (IRR), the payback period (PBP), and the net present value (NPV) are 12.4%, 7 years and 6 million USD, respectively. The result shows that the IRR value is greater than bank interest which indicates that the EFB Biorefinery has good potential in terms of economic viability. The selling price of glucose used in this economic analysis is selected based on the consideration that glucose will be used as raw material for bioethanol production so that the price of bioethanol produced can compete with market price. The demand for bioethanol in Indonesia is quite high, especially after the government decree the mandatory use of bioethanol fuel into conventional fuel mixtures, as stated in MEMR (The Ministry of Energy and Mineral Resources) Regulation No. 12/2015. This also indicates that the biorefinery technology where multiple products are produced plays a crucial role in enabling the production of cheap glucose, and consequently cheap bioethanol fuel or other glucose derivatives where the price can compete with fossil derived products.

| Table 5. Economic analysis result. |
|-----------------------------------|
| IRR                               | 12.4% |
| Payback period                    | 7 years |
| Net Present Value                 | $ 6 million |

3.3. Palm oil circular bioeconomy in Indonesia and the role of EFB biorefinery technology

Circular bioeconomy (CBE) concept, which is the combination of circular economy and bioeconomy, is introduced to achieve a resource-efficient biomass utilization by focusing on the use of biomass residues and wastes as resources and integrating several bio-based processes to achieve high value application of biomass. Moreover, it also focuses on extending product lifespan through improved design and servicing, and using resources more efficiently by using them over and over [28, 35].
Utilization of EFB into high-value added products has manifold roles in the circular bioeconomy in Indonesia. Firstly, it relocates waste from the end of supply chain to the feedstock. Secondly, it adds value from a relatively low-value bioproducts into high-value bioproducts. Thirdly, it replaces some products derived from fossil resources which consequently reduces Indonesia dependency on external sources [27, 28].

Figure 4 shows the industrial concept of EFB utilization. EFB biorefinery plant will be built near the palm oil mill. EFBs will either be washed, dried and shredded in palm oil mill prior to transfer to biorefinery plant or will be transferred directly to biorefinery plant to be processed there. Since the location of the mill and biorefinery plant are close to each other, some facilities such as the feed handling, storage and utilities can be combined, thus minimizing the capital investment cost. Additionally, the cost for feedstock transportation, which gives relatively high contribution to the operational cost due to the low density of EFB [18], can also be reduced. Shredded EFBs are then fractionated and converted into glucose, xylose, and lignin in EFB biorefinery plant. These precursors will then be transported and distributed to related upstream or downstream industries for further processing into intermediates or end products. The solid residue as by-product of biorefinery plant contains some nutrients which are beneficial for the soil, thus can be used as a complement to fertilizer. Since the location of biorefinery plant is close to palm oil plantation, the transportation cost for the solid residue application as fertilizer is negligible.

3.3.1. Benefit. There are several positive impacts of EFB circular bioeconomy in Indonesia in terms of economic, environmental and social impacts. Economically, EFB biorefinery plant could trigger the development of bio-based downstream industries in Indonesia to meet the increasing demand for bio-based products, thereby increasing the production volume and the country’s Gross Domestic Product. As the awareness of investors and consumers about sustainable and environmentally benign products increases, the demand for bio-based products will increase.

EFB derivative products, such as 2,3-butanediol, lactic acid, ethanol, sorbitol, lysine, succinic acid, lactic acid, acetone, gluconic acid which are glucose derivative products; xylitol, furfural, and levulinic acid which are xylose derivative products; as well as benzene, toluene, and xylene, which are lignin derivative products, are classified as the top value-added bio-based chemicals based on its market demand, market size, and commercial application [3]. Currently, the fulfillment of these products in
Indonesia depends on foreign supply with total import value reached USD 500 million [36]. The development of EFB biorefineries in Indonesia will accelerate the development of its downstream industries, thereby strengthening Indonesia's sovereignty in energy, food and chemical production. In addition, as a country having the second largest peatland area amounting to 22.5 million ha [37], Indonesia has the potential to supply bio-based products not only domestically, but also globally.

Environmentally, the use of EFB as a replacement of non-renewable material could mitigate the climate change. EFB derivative products have the potential to replace the conventional products produced from non-renewable raw materials, which will significantly contribute to the reduction of greenhouse gasses emissions. Furthermore, it also reduces Indonesia dependency on non-renewable raw materials, particularly on food, chemical, and energy sectors.

Socially, the use of EFB as biorefinery feedstock could ensure the food security. Unlike first-generation ethanol which is produced from food, EFB is an agricultural waste therefore its utilization does not compete with food. Additionally, the development of EFB biorefineries will trigger the growth of the downstream industries, thus creating more jobs for Indonesian people. The biorefinery plant itself is proposed to be built near an established palm oil mill and plantations and will therefore absorb local workers. This will create jobs for thousands of people and consequently increasing the well-being of the people in Indonesia.

3.4. EFB biorefinery as part of Making Indonesia 4.0

In order to strengthen the manufacturing sector in Indonesia for making Indonesia as the top 5 global economy, the government plans to implement I4.0 in Indonesia as outlined in the “Making Indonesia 4.0” program. Several commitments are made by the government to successfully implement this program which includes doubling the productivity to cost ratio, increasing exports to 10% of GDP, and increasing the allocation of R&D funds to 2% of GDP [30]. There are five main industrial sectors prioritized in the “Making Indonesia 4.0” program which includes food and beverages, chemical, textile, automotive, and electronic [31]. EFB biorefineries play an important role in supporting the successful and long-term implementation of “Making Indonesia 4.0” because the biorefineries can act as a trigger for the development of the downstream industries in Indonesia, particularly in food, energy and chemical sectors, replacing the non-renewable with bio-based products, thereby reducing Indonesia dependency on non-renewable source and strengthening Indonesia's sovereignty in energy, food and chemical sectors. Further, some long-term benefits of the implementation of “Making Indonesia 4.0”, which are expected to happen, are (1) the increase in the production volume thereby increasing the country’s GDP, (2) higher investment on technology research & development which can further support the growth of the industry to achieve higher productivity and efficiency, and move towards cleaner energy, and (3) higher living quality and education standard of the people in Indonesia [30].

4. Conclusion

The integrated EFB biorefinery technology concept through sequence fractionation of main components of EFB shows a good potency to be applied in industrial scheme, for the production of various bio-based chemicals and biofuel as an alternative to conventional ones. The economic analysis shows that EFB biorefinery with capacity as much as 60 k-ton/year has an IRR of 12.4%, payback period of 7 years, and NPV of 6 million USD at selling price of concentrated glucose, xylose and lignin 113.00, 308.70, and 594.01 USD per ton, respectively. Furthermore, the advances of this technology in Indonesia will provide several benefits, such as connecting various oil palm-based research in Indonesia, thus accelerating the commercialization of these research, as well as strengthening Indonesia's sovereignty in energy, food and chemical sectors, helping to move toward circular bioeconomy, increasing the country’s GDP, and elevating the well-being of Indonesian people.

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