Technical Paper

Special articles: Asian Conference on Biomass Science I

特集：アジアバイオマス科学会議 I

Oil Palm Empty Fruit Bunch as a Promising Feedstock for Biorefinery Products: A Holistic Approach with Economic, Energy, and Environmental Consideration

Agusta Samodra PUTRA^{*1}^{*}², Ryoza NOGUCHI^{*3}[†], Tofael AHAMED^{*3}, and Hiroshi OHI^{*3}

(Received January 9, 2020)

The oil palm empty fruit bunch (EFB) is a rich carbon-source material that can be considered as a valuable candidate for several applications. Recently, EFB has been used as an organic compost fertilizer in oil palm plantations. The life cycle assessment (LCA), life cycle cost (LCC), and cumulative energy demand (CED) were used to evaluate the feasibility of EFB as a raw material for dissolving pulp and furfural co-production. An additional techno-economic assessment was performed on realistic industrial-scale process conditions for cost calculation. In the production of 1 kg dissolving pulp with the co-production of 0.01 kg furfural, -1.218 kg CO₂ eq of global warming potential (GWP100), -0.006 kg SO₂ eq of acidification potential (AP), -0.002 kg PO₄³⁻ eq of eutrophication potential (EP), -0.054 kg 1,4-DB eq of human toxicity potential (HTP) and 1.887 MJ of cumulative energy demand (CED) were generated. The economic assessment indicated that the production of 1 kg dissolving pulp in the proposed product system resulted in earnings of 71.11 JPY based on LCC methodology and earnings of 54.44 JPY in the techno-economic assessment simulation after 15 years. The application of the *waste-to-product* concept for EFB via biorefinery processes, such as dissolving pulp and furfural co-production, offer advantages in terms of economic, environmental, and energy requirements.

近年、オイルパームの空果房 (EFB) は、オイルパームプランテーションの有機堆肥の原料として利用されているが、EFBは豊富な炭素源物質であり、有機堆肥以外の用途に対する貴重な原料と考えられている。本論文では、環境影響評価 (LCA)、ライフサイクルコスト計算 (LCC)、累積エネルギー需要量 (CED) を用いて、EFBを原料とした、溶解パルプとフルフラールの共同生産の実現可能性を評価した。さらに、コスト計算のために、現実的な産業規模のプロセス条件での技術経済評価を実施した。

EFBによる溶解パルプ 1 kg とフルフラール 0.01 kg の生産では、地球温暖化ポテンシャル (GWP100) の CO₂ 換算で -1.218 kg、酸性化ポテンシャル (AP) の SO₂ 換算で -0.006 kg、栄養化ポテンシャル (EP) の PO₄³⁻ 換算で -0.002 kg、人間毒性ポテンシャル (HTP) の 1,4-DB 換算で -0.054 kg、CED として 1.887 MJ が発生した。経済評価の結果、EFB から溶解パルプ 1 kg を生産した場合、LCC による収益は 71.11 円、15 年後の技術経済評価シミュレーションによる収益は 54.44 円となった。このように、EFB を原料とした溶解パルプとフルフラールの共同生産の評価結果から、廃棄物のバイオリファイナリープロセスによって付加価値の高い製品を製造することは、経済性、環境性、エネルギー面でメリットが高いと考えられる。

Key Words

Empty Fruit Bunch (EFB), Life Cycle Assessment (LCA), Life Cycle Cost (LCC), Cumulative Energy Demand (CED), Techno-economic analysis

※1 Graduate School of Life and Environmental Sciences,
University of Tsukuba
Tennodai, Tsukuba-shi, Ibaraki 305-8572, Japan

※2 Research Center for Chemistry,
Indonesian Institute of Sciences, Indonesia

※3 Faculty of Life and Environmental Sciences,
University of Tsukuba
Tennodai, Tsukuba-shi, Ibaraki 305-8572, Japan

† Corresponding author: noguchi.ryoza.gm@u.tsukuba.ac.jp

1. Introduction

Indonesian oil palm plantation areas are mainly located in Sumatra and Kalimantan islands. The distribution of oil palm plantations in Indonesia is shown in Fig. 1. Riau Province possesses the largest oil palm plantation area among provinces in Indonesia, and there were 2.4 million ha of oil palm plantations in 2016¹⁾. The oil palm fresh fruit bunch is used as a raw material in crude palm oil (CPO) mills. The CPO mills in Indonesia release empty fruit bunch (EFB) as waste. The scheme of CPO production is shown in Fig. 2. Recently, EFB is used as an organic compost fertilizer in oil palm plantations^{2)~5)}.

Specifically, EFB is a rich carbon-source material that can be considered as a valuable material in the future. As shown in Table 1, the main chemical composition of EFB consists of cellulose (glucan), hemicellulose (xylan) and lignin. Efforts focused on processing EFB into valuable products via mechanical and chemical treatments.

Mechanical treatment such as drying, shredding and pressing the EFB into briquettes, is a possibility in the EFB valorization pathway^{6)~7)}. The obstacle to the

mechanical treatment is the high moisture content of EFB (approximately 50%) which in turn is inefficient.

Additionally, chemical treatment (e.g., chemical cooking or pulping for converting EFB into valuable biorefinery products) can be promoted as opposed to mechanical treatment. The abundance of cellulose and hemicellulose in the EFB can be converted into biorefinery products such as dissolving pulp (cellulose pulp) and furfural from hemicellulose. Dissolving pulp is a raw material for cellulosic fibers and is used as an alternative to cotton,

Table 1 Chemical composition of Empty Fruit Bunch (EFB)

Parameter	Composition based on dry weight EFB (%)		
	1 ¹⁾	2 ¹²⁾	3 ¹³⁾
Lignin	31.0	29.6	29.6
Glucan	31.1	35.1	35.7
Xylan	17.5	19.8	20.1
Other sugars	0.8	1.9	1.6
Extractive	8.6	5.4	7.1
Ash	5.5	5.9	5.5
Unknown	5.5	2.3	2.4

1: Putra *et al.*; 2: Nakagawa-izumi *et al.*; 3: Harsono *et al.*

Fig. 1 Oil palm plantation area in Indonesia¹⁾

Fig. 2 CPO production process and EFB utilization scheme

specialty papers, and viscose clothing⁸⁾. Currently, the dissolving pulp production is only derived from wood-based raw materials. The dissolving pulp production was established since the 1950s via acid sulfite or prehydrolysis-kraft processes⁹⁾.

Additionally, furfural is a diversified product from hemicellulose and is identified as one of the top thirty platform chemicals that can be made from biomass¹⁰⁾. It is used as a selective solvent for separating saturated compounds in petroleum refining. In extant studies, biomass is used for furfural production. It was produced from EFB¹⁴⁾, rice husk¹⁵⁾, corn cobs¹⁶⁾ and sorghum straw¹⁷⁾.

The market price of dissolving pulp and furfural exceeds that of compost fertilizer and briquette. However, it is necessary to prove that EFB-based biorefinery production is feasible. Feasibility studies on the production have been conducted in recent years^{18) 19)}, but a complete feasibility study should consider environmental, energy usage, and economic aspects.

An integrated life cycle assessment (LCA)-life cycle cost (LCC)-energy assessment can comprehensively provide a precise interpretation of the production system scenario for a company or decision-maker. Life-cycle thinking is required for the feasibility study. It is applied in LCA to assess the environmental impact of the product, in LCC to assess the cost of production through the product's life cycle, and in cumulative energy demand (CED) method to assess primary energy usage through the product life cycle following the LCA framework. The goal of the study is to evaluate EFB as a promising feedstock for dissolving pulp and furfural co-production while considering environmental effects, energy usage, and economic parameters.

The assessment of environmental effects and energy consumption in pulp and paper industry has been performed^{20) 22)}. However, utilizing EFB as a raw material to substitute wood in dissolving pulp production and integrating economic analysis in the LCA framework are the novel

contributions of the present study. The proposed EFB-based dissolving pulp production is still at the lab-scale development stage. However, the proposed process is necessary because non-wood dissolving pulp process production can lead to improved environmental outcomes^{23) 24)}.

2. Methodology

The LCA methodology was based on ISO 14040 to evaluate the environmental impact of EFB valorization as a raw material for biorefinery products such as dissolving pulp and furfural. The inventory data framework used to calculate LCA was used for economic and energy analysis of using LCC and CED, respectively. The overall methodology is shown in Fig. 3. The methodology consists of goal and scope definitions; environmental, economic and energy aspect assessments; and interpretation of each result. We discuss global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), human toxicity potential (HTP), and CED.

2.1 Goal and scope for LCA, LCC, and CED

The goal of the feasibility study is to evaluate the environmental impact, CED, and LCC of dissolving pulp production by using prehydrolysis/soda-anthraquinone (AQ) cooking followed by elemental chlorine-free (ECF) bleaching. This is necessary to prove that EFB is a promising feedstock for substituting wood chips in the dissolving pulp production process.

The LCA study followed system expansion from oil palm plantation (EFB extraction) to dissolving pulp product and furfural co-product in the consequential approach. Fig. 4 shows a system boundary for the consequential life cycle framework for EFB to dissolving pulp production. This shows the proposed system boundary for dissolving pulp production from EFB that affects the conventional dissolving pulp production system. As previously mentioned, conventional dissolving pulp production is only derived

Fig. 3 Scheme of the methodology in this research

Fig. 4 Simulation of consequential LCA approach in the dissolving pulp production process

from wood. The sustainability of the raw material must be considered. The selection of EFB as a raw material decreases the utilization of wood. This is a consequential point in the study.

2.2 Calculation

Functional unit determination as a basis calculation corresponds to the most important part of LCA, LCC, and CED studies. In the study, 1 kg of dissolving pulp was used as a functional unit. The baseline environmental impact categories, such as climate change or GWP in kg CO₂ equivalent (eq) unit, EP in kg PO₄³⁻ eq unit, AP in kg SO₂ eq unit, and HTP in kg 1,4-dichlorobenzene (1,4-DB) eq unit, were quantified. The global warming potential is related to emissions of greenhouse gases (GHG) and is frequently expressed as time span variation generally in 20, 50, and 100 years (GWP20, GWP50, GWP100). Of these, GWP100 was used in the study. Eutrophication potential corresponds to the prediction for over-accumulation of nutrients. Acidification potential corresponds to the prediction of the over-accumulation of acidifying substance in the environment. Human toxicity potential is related to its effect on human health of toxic substances present in the environment²⁵. The LCA calculation for environmental impact in each category is based on equation (1)²⁵, as follows:

$$\text{Environmental Impact} = \sum (E \times f_{\text{substance}}) \quad (1)$$

Specifically, E denotes emission in kg/kg of the functional

unit; and $f_{\text{substance}}$ denotes the emission characterization factor.

The emission characterization factor for climate change (GWP100) environmental impact category followed the characterization model as developed by the Intergovernmental Panel on Climate Change (IPCC)²⁵. The factor was expressed in kg CO₂ eq/kg of emission. The eutrophication potential (EP) characterization factor was based on the stoichiometric procedure of *Centrum voor Milieuwetenschappen Leiden* (CML) impact assessment method and was expressed as kg PO₄³⁻ eq/kg of emission²⁶. The AP characterization factor for emissions to air was calculated based on the Regional Air Pollution Information and Simulation (RAINS) 10 model in the kg SO₂ eq/kg of emission expression²⁷. The HTP characterization factor was calculated based on the Uniform System for the Evaluation of Substance adapted for LCA purposes (USES-LCA) and expressed as 1,4-dichlorobenzene eq/kg of emission²⁸.

The LCC uses the same life cycle inventory data framework for the direct (foreground) process. The value depends on the total cost of material and energy through its life cycle. The calculation of LCC corresponds to equation (2)²⁹ as follows:

$$\text{LCC} = \sum (Q \times P) \quad (2)$$

Specifically, Q denotes the quantity of energy or material through the product life cycle (MJ energy or kg material); and P denotes the price of energy or material per unit value (JPY/MJ or JPY/kg).

Fig. 5 Technical process diagram block of dissolving pulp and furfural co-production

In the case of wood raw material replacement in the same dissolving pulp mill, additional indirect costs including new equipment investment and labor were not calculated. However, an additional case scenario including indirect costs was also performed in the study as techno-economic analysis (TEA) for dissolving pulp mill investment. The annual earnings parameter was used as a techno-economic performance indicator in the study. The annual earnings were calculated using equation (3a) and (3b)³⁰.

Annual earning = Annual revenues

$$- [\text{Operating costs} + (a \times \text{Investment costs})] \quad (3a)$$

where

$$a = \frac{i}{1 - (1 + i)^{-n}} \quad (3b)$$

where i is the interest rate

Equipment investment cost was calculated based on the six-tenth rule in equation (4)³¹ as follows:

$$\text{New Cost} = \text{Original Cost} \left(\frac{\text{New Size}}{\text{Original Size}} \right)^{0.6} \quad (4)$$

The total cumulative energy input to the utilization of EFB for dissolving pulp and furfural co-production was assessed via the CED method. The CED represents the direct and indirect energy use throughout its life cycle including the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials³². Generally, the life cycle of a product is subdivided into three phases corresponding to 'production' (P), 'use' (U) and 'disposal' (D). Thus, the total CED input corresponds to equation (5)³³.

$$\text{CED} = \text{CED}_p + \text{CED}_U + \text{CED}_D \quad (5)$$

SimaPro v8.0.5 from Pré-sustainability was used for LCA and CED analysis in the study. The production of 1 kg dissolving pulp was selected as the functional unit in the study.

2.3 Data collection

Data on input-output direct material and energy inventory, prices, operational conditions, and investment were collected from the literature review and lab-scale experiments for dissolving pulp and furfural production in the previous publications^{11) 13)}. The technical process condition on EFB-based dissolving pulp process production

Table 2 Bleaching conditions for proposed process¹³⁾

Bleaching sequence	Process conditions
D ₀	ClO ₂ dosage 2.9%; 1 h; 70 °C; PC* 10%
E _p	NaOH dosage 1%; H ₂ O ₂ dosage 1.4%; 1 h; 70 °C; PC* 10%
D ₁	ClO ₂ dosage 0.5%; 1 h; 70 °C; PC* 10%

*PC: Pulp Consistency; D₀: chlorine dioxide bleaching; E_p: extraction with peroxide; D₁: smaller dosage of chlorine dioxide bleaching than D₀

via prehydrolysis/soda-AQ cooking followed by ECF bleaching is shown in Fig. 5. Based on the lab-scale experiment in the previous research, the EFB was first pre-treated via a prehydrolysis process using water with 7 mL/g liquor-to-solid ratio at 150 °C for 3 h. After prehydrolysis, the wet solid residue of EFB was subjected to soda-AQ cooking for 3 h at 160 °C with 20% active alkali dosage and 0.1% AQ dosage. The process was followed by the ECF bleaching process that consisted of D₀-E_p-D₁ (D₀: chlorine dioxide bleaching; E_p: extraction with peroxide; D₁: smaller dosage of chlorine dioxide bleaching than D₀). The bleaching conditions are listed in Table 2.

In the prehydrolysis process, prehydrolysis liquor (PHL) was generated as high hemicellulose content liquor. It was subjected to dehydration process for 1 h at 98 °C with acid catalyst addition to produce furfural¹¹⁾. This furfural was considered to be a co-product in the study.

Other supporting data such as EFB plantation, dissolving pulp manufacturing location and material transportation in LCA, LCC and CED calculations were selected based on the condition of oil palm plantation and wood-based dissolving pulp industry in Riau Province. An industrial field study of this conventional dissolving pulp industry was conducted to input additional technical information related to industrial-scale process conditions. It was necessary to construct a reliable techno-economic analysis.

3. Results and Discussion

Based on the system boundary described in Fig. 4, the EFB is allocated as waste in the CPO product system. It is used as a raw material to substitute wood chips in

dissolving pulp production. In lab-scale production, an EFB-based dissolving pulp was fabricated, and the same level of conventional dissolving pulp quality was obtained¹³⁾. Thus, the raw material shifted from wood chips to EFB in the LCA, LCC, and CED calculations was reliable.

The life cycle input-output inventory analysis was performed for the direct (foreground) process in the study. The inventory data contained all materials and energy systems in the dissolving pulp and furfural co-production. It was used for LCA, CED, and LCC calculations and externalities, such as investment cost and labor cost, were excluded. **Table 3** shows input-output material and energy to produce 1 kg of dissolving pulp. In the life cycle inventory analysis, 5.29 kg of EFB (50% moisture content) was required to produce 1 kg of dissolving pulp (air-dried basis) based on lab-scale production yield (34%). In the conventional process in the industry, 4.5 kg of wood was required to produce 1 kg of dissolving pulp (40% yield). It was concluded that 4.5 kg of wood extraction can be substituted by 5.29 kg of EFB waste valorization to produce 1 kg of dissolving pulp. Thus, it was considered as a negative value consequence in the process input of life cycle inventory analysis.

The environmental impact was calculated based on input-output mass and energy in the life cycle inventory analysis. The dissolving pulp and furfural were determined

as the main product and co-product, respectively. The environmental impact and CED calculation followed the system boundary of consequential LCA, as shown in Fig. 4.

The total values of GWP100, AP, EP, and HTP were negative in the production of 1 kg dissolving pulp from EFB via prehydrolysis/soda-AQ cooking followed by ECF bleaching. SimaPro v8.0.5 software was used, and -1.218 kg CO₂ eq of GWP100, -0.006 kg SO₂ eq of AP, -0.002 kg PO₄³⁻ eq of EP and -0.054 kg 1,4-DB eq of HTP were generated to produce 1 kg of dissolving pulp from EFB. The values imply that the proposed production system provided an advantage to the environmental system in terms of greenhouse gases, nutrients, acidifying substances, and toxic substances emission reduction in comparison with the conventional dissolving pulp production. This proved that the EFB-based dissolving pulp production was environmentally feasible.

The CED analysis was conducted in the study of non-renewable energy source usage. Specifically, 1.887 MJ of CED was generated in the production of 1 kg dissolving pulp from EFB with the same framework as LCA analysis. This implies that the proposed production system potentially decreased primary energy usage through its life cycle. The conventional dissolving pulp production from wood required 33.205 MJ of CED. This proved that the proposed process was feasible from an energy-conservation point of view.

For comparison purposes, other researchers reported

Table 3 Life cycle inventory and life cycle cost analysis to produce 1 kg of dissolving pulp

	Unit	Value	Price per Unit (JPY)	LCC (JPY)
Input				
Material				
EFB, 50% moisture	kg	5.294	0.00	0.00
Wood chips, 50% moisture	kg	-4.500	6.50 ³⁴⁾	-29.25
H ₂ O ₂	kg	0.013	41.00 ³⁵⁾	0.53
NaOH for cooking	kg	0.683	37.00 ³⁶⁾	25.27
NaOH for bleaching	kg	0.009	37.00 ³⁶⁾	0.33
Chlorine dioxide	kg	0.035	60.00 ³⁷⁾	1.86
Water	m ³	0.073	120.00 ³⁸⁾	8.76
Sulfuric acid	kg	1.112	21.30 ³⁹⁾	23.69
Anthraquinone	kg	0.003	550.00 ⁴⁰⁾	1.65
Energy				
Electricity	kWh	0.443	8.30 ⁴¹⁾	3.68
Steam	kWh	2.222	2.22 ⁴²⁾	4.89
Transportation				
Truck	t km	0.265	24.00*	6.36
Total LCC from input				47.77
Output				
Dissolving pulp (air dried)	kg	1.000	100.00 ⁴³⁾	100.00
Furfural (co-product)	kg	0.011	1785.00 ⁴⁴⁾	18.88
CO ₂	kg	0.079	0.00**	0.00
Total revenue from output				118.88

* Truck cost for 5 t of capacity and 50 km distance (short distance) is 6000 JPY in Indonesia

** Carbon tax has not been applied yet in Indonesia

that conventional acid sulfite-based totally chlorine-free (TCF) bleaching dissolving pulp production from wood chips resulted in higher environmental impacts when compared to the proposed process⁸). Their study indicated that the total environmental impact to produce 1 kg of dissolving pulp in their process corresponded to 0.415 kg CO₂ eq of GWP100, 0.002 kg PO₄³⁻ eq of EP, 0.005 kg SO₂ eq of AP and 0.072 kg 1,4-DB eq of HTP⁸). However, there is a paucity of studies that report on LCA results in the prehydrolysis kraft-based ECF bleaching dissolving pulp production which is similar to that in the conventional dissolving pulp mill in Indonesia.

Another advantage of applying lignocellulosic materials, such as EFB, is that it is easier to delignify when compared to wood⁴⁵) and, softer cooking processes, such as soda cooking, can be applied to EFB. In contrast to the kraft-based or acid sulfite-based method that is generally used in the conventional dissolving pulp production, soda cooking corresponds to a sulfur-free cooking process. Thus, it decreases acidifying substance emissions.

The LCC was calculated by following the LCA framework. The total LCC from material and energy input in the study corresponded to 47.77 JPY to produce 1 kg of dissolving pulp. The total revenue corresponded to 118.88 JPY and is due to the selling price of 1 kg dissolving pulp and 0.011 kg furfural. This implies that EFB-based dissolving pulp and furfural co-production earned 71.11 JPY per 1 kg of dissolving pulp production in the LCC calculation. The unit price per kilogram of dissolving pulp corresponded to 100 JPY while the unit price per kilogram of furfural corresponded to 1785 JPY. Given the economic value comparison, the production of furfural as prehydrolysis waste valorization is necessary. Chemicals, such as NaOH for the cooking process and sulfuric acid for furfural production are the main contributors to LCC. The optimization of process chemical usage while maintaining product quality in the proposed product system is necessary.

Another advantage of applying this proposed product system in Indonesia is that the largest oil palm plantation and the existing dissolving pulp industry are in the same location, in Riau Province, Sumatra, Indonesia. Therefore, the proposed technology can be scaled-up to an industrial scale without further investment. Additionally, the life cycle inventory analysis in Table 3 shows that the transportation for material transfer contributed to 12.65% in the LCC. This implies that a longer distance for material transfer transportation significantly affect the LCC.

The assumption in the LCC analysis was that EFB-based dissolving pulp production does not change the existing dissolving pulp mill equipment in Riau Province. Moreover, the LCC analysis in the study only focused on

the direct (foreground) process, excluding the indirect cost.

Thus, additional techno-economic analysis was conducted by considering the investment to construct the new dissolving pulp and furfural plant. In the study, a new investment in integrated dissolving pulp and furfural plant with 250,000 ADt/y dissolving pulp production capacity was simulated. The economic parameters for techno-economic assessment in the study are listed in Table 4.

The economic performance parameter in the study was the annual earnings. The lifetime of all invested equipment was assumed as 15 years in the study with a 7% bank interest rate. The interest rate was based on the average bank interest rate in Indonesia. The number of working days per year was assumed as 330 days. The same mass and energy balance as that in life cycle inventory analysis in Table 3 is applied for most operational cost calculations. At the industrial scale, the chemicals need to be recovered. In the study, the chemical recovery efficiency was assumed as 80-90%.

The annual earnings within 20 years in the same functional unit as LCA, CED and LCC calculation is shown in Fig. 6. The first year was considered as the construction period and the next 2 years were considered as the trial period. The maximum production capacity was not obtained during the trial period. In the study, the production capacity was assumed as 50% and as 75% in the second and third years, respectively.

Based on annual earnings simulation for new plant of integrated dissolving pulp and furfural production in Fig. 6, positive annual earnings are obtained from third-year production. The annual earnings in third-year period were 743 billion JPY. This implies an earnings of 29.71 JPY per kilogram of dissolving pulp production based on the techno-economic assessment that described the realistic simulation of EFB-based dissolving pulp production. Annual earnings increased due to the depreciation in investment costs.

In the techno-economic assessment, the profit per kilogram of dissolving pulp production corresponded to 54.44 JPY as obtained after 15 years. The amount was slightly lower than the profit in the LCC methodology. This was due to the exclusion of indirect costs in the LCC study. The integration of techno-economic assessment and LCC can constitute a useful tool to obtain a more comprehensive economic assessment interpretation in the study.

Based on the overall assessment consideration, the valorization of EFB as the feedstock for dissolving pulp production was attractive and feasible. It offers advantages in terms of environmental, energy usage, and economic considerations.

Table 4 Economic parameters used in the techno-economic analysis in the study

Parameter	Unit	Value
Equipment lifetime	y	15
Interest rate, i	%	7
Annuity factor		0.11
Scale factor		0.6
Dissolving pulp production capacity	ADt/y	250,000
Furfural production capacity	t/y	2,645
Working day per year	d	330
Construction	y	1
Trial production period	y	2
Price of dissolving pulp	JPY/ADt	100,000
Price of furfural	JPY/ADt	1,785,000
<i>Investment costs</i>		
Digester for dissolving pulp production ³¹⁾	JPY	2,764,667,090
Furfural plant ⁴⁶⁾	JPY	209,341,039
Recovery boiler ³¹⁾	JPY	8,250,000,000
Causticization plant and lime kiln ³¹⁾	JPY	2,887,541,183
Heat exchanger system ³⁰⁾	JPY	303,600,000
Piping	JPY	122,100,000
<i>Operating costs</i>		
Total chemicals	JPY/y	7,589,950,000
Electricity	JPY/y	919,225,000
Steam production	JPY/y	1,233,210,000
Total water	JPY/y	2,550,000,000
Transportation	JPY/y	1,590,000,000
Labor cost	JPY/y	48,000,000
Maintenance cost for digester plant	JPY/y	27,646,671
Maintenance cost for furfural plant	JPY/y	2,093,410
Maintenance cost for recovery boiler	JPY/y	82,500,000
Maintenance cost for heat exchanger	JPY/y	3,036,000
Maintenance cost for piping	JPY/y	1,221,000
Maintenance cost for causticization plant and lime kiln	JPY/y	28,875,412

Fig. 6 Costs analysis for 1 kg of dissolving pulp production in the study

4. Conclusion and Recommendations

The application of *waste-to-product* concept for EFB via biorefinery processes, such as dissolving pulp and furfural co-production, offers advantages in terms of economic, environmental, and energy consideration. In the production of 1 kg dissolving pulp with the co-production of 0.01 kg furfural, -1.218 kg CO₂ eq of GWP100, -0.006 kg SO₂ eq of AP, -0.002 kg PO₄³⁻ eq of EP and -0.054 kg 1,4-DB eq of HTP were generated in the product system. These values imply that the proposed production system exhibits an advantage to the environmental system. In the same functional unit, the CED analysis exhibited a cumulative energy demand corresponding to 1.887 MJ. Two economic assessments were conducted in the study. They indicated that the production of 1 kg dissolving pulp in the proposed product system yields 71.11 JPY as earnings based on LCC methodology and 54.44 JPY as earning obtained after 15 years in the techno-economic assessment simulation.

The valorization of EFB and decrease in the wood chips demand in the dissolving pulp production correspond to key advantages of EFB utilization as feedstock for dissolving pulp and furfural co-production. However, the proposed process is still in the initiation phase and a feasibility study with more complexities is required for future research.

References

- 1) Ditjenbun, Tree crop estate statistics of Indonesia: 2015-2017 palm oil. Indonesian Ministry of Agriculture, (2016)
- 2) Nasution, M. A.; Wibawa, D. S.; Ahamed, T.; Noguchi, R., *J Cleaner Prod*, **184**, 1028-1040 (2018)
- 3) Siddique, S.; Shafawati, S. N.; Naher, L., *Biotechnol Rep*, **13**, 1-7 (2017)
- 4) Yoshizaki, T.; Shirai, Y.; Hassan, M. A.; Baharuddin, A. S.; Abdullah, N. M. R., *J Cleaner Prod*, **44**, 1-7 (2013)
- 5) Chiew, Y. L.; Shimada, S., *Biomass Bioenergy*, **51**, 109-124 (2013)
- 6) Vaskan, P.; Pachón, E. R.; Gnansounou, E., *J Cleaner Prod*, **172**, 3655-3668 (2018)
- 7) Hosseini, S. E.; Wahid, M. A., *Renew Sustain Energy Rev*, **40**, 621-632 (2014)
- 8) Gonzáles-García, S.; Hospido, A.; Agnemo, R.; Svensson, P.; Selling, E.; Moriera, M. T.; Feijoo, G., *J Ind Ecol*, **15**(4), 568-583 (2011)
- 9) Sixta, H.; Iakolev, M.; Testova, L.; Roselli, A.; Hummel, M.; Borrega, M.; van Heiningen, A.; Froschauer, C.; Schottenberger, H., *Cellulose*, **20**, 1547-1561 (2013)
- 10) Cai, C.M.; Zhang, T.; Kumar, R.; Wyman, C. E., *J Chem Technol Biotechnol*, **89**, 2-10 (2014)
- 11) Putra, A.S.; Nakagawa-izumi, A.; Kajiyama, M.; Ohi, H., *Jpn TAPPI J*, **72**(6), 641-649 (2018)
- 12) Nakagawa-izumi, A.; H'ng, Y. Y.; Mulyantara, L. T.; Maryana, R.; Do, V. T.; Ohi, H., *Ind Crops Prod*, **95**, 615-620 (2017)
- 13) Harsono; Putra, A. S.; Maryana, R.; Rizaluddin, A. T.; H'ng, Y. Y.; Nakagawa-izumi, A.; Ohi, H., *J Wood Sci*, **62**, 65-73 (2016)
- 14) Raman, J. K.; Gnansou, E., *Ind Crops Prod*, **69**, 371-377 (2015)
- 15) Suxia, R.; Haiyan, X.; Jinling, Z.; Shunqing, L.; Xiaofeng, H.; Tingzhou, L., *Carbohydr Res*, **359**, 1-6 (2012)
- 16) Sánchez, C.; Serrano, L.; Andres, M. A., Labidi, J., *Ind Crops Prod*, **42**, 513-519 (2013)
- 17) Vazquez, M.; Oliva, M.; Tellez-Luis, S. J.; ramirez, J. A., *Bioresour Technol*, **98**, 3053-3060 (2007)
- 18) Reeb, C. W.; Hays, T.; Venditti, R. A.; Gonzales, R.; Kelley, S., *BioResources*, **9**(3), 5385-5416 (2014)
- 19) Onoja, E.; Chandren, S.; Razak, F. I. A.; Mahat, N. A.; Wahab, R. A., *Waste and Biomass Valorization*, **10**, 2099-2117 (2019)
- 20) Gaudreault, C.; Samson, R.; Stuart, P. R., *Int J Life Cycle Assess*, **15**, 198-211 (2010)
- 21) Pineda-Henson, R.; Culaba, A. B.; Mendoza, G. A., *J Ind Ecol*, **6**(1), 15-28 (2002)
- 22) Lopes, E.; Dias, A. C.; Arroja, L.; Capela, I.; Pereira, F., *J Cleaner Prod*, **11**, 51-59 (2003)
- 23) Andrade, M. F.; Colodette, J. L., *Ind Crops Prod*, **52**, 58-64 (2014)
- 24) Das, A. K.; Nakagawa-izumi, A.; Ohi, H., *Carbohydr Polym*, **147**, 133-138 (2016)
- 25) Guinée, J., Handbook on Life Cycle Assessment, Kluwer, 2001
- 26) PRé, SimaPro Database Manual Methods library, PRé-Sustainability, 2019
- 27) Kelly, J. A., An Overview of the RAINS Model, Environmental Protection Agency, 2006
- 28) van Zelm, R.; Huijbregts, M. A. J.; van de Meent, D., *Int J Life Cycle Assess*, **14**, 282-284 (2009)
- 29) Heijungs, R.; Settnani, E.; Guinée, J., *Int J Life Cycle Assess*, **18**, 1722-1733 (2013)
- 30) Laaksonen, C.; Axelsson, E.; Berntsson, T.; Lundström, A., *Clean Techn Environ Policy*, **11**, 77-82 (2009)
- 31) Lundberg, V.; Bood, J.; Nilsson, L.; Axelsson, E.; Berntsson, T.; Svensson, E., *Clean Techn Environ Policy*, **16**, 1411-1422 (2014)
- 32) Huijbregts, M. A. J.; Rombouts, L. J. A.; Hellweg, S.; Frischknecht, R.; Hendriks, A. J.; Van de Meent, D.; Ragas, A. D. M. J.; Reijnders, L.; Struijs, J., *Environ Sci and Technol*, **40**(3), 641-648 (2006)
- 33) Röhrlich, M.; Mistry, M.; Martens, P. N.; Buntentbach, S.

- Ruhrberg, M.; Dienhart, M.; Briem, S.; Quinkertz, R.; Alkan, Z.; Kugeler, K., *Int J Life Cycle Assess*, **5**(6), 369-373 (2000)
- 34) Alibaba global online trading website, http://www.alibaba.com/product-detail/Eucalyptus-wood-chip-wood-pulp_50041387241.html (Last access: February 21, 2020)
- 35) Alibaba global online trading website, http://www.alibaba.com/product-detail/Wholesale-bulk-hydrogen-peroxide-50-price_62083106700.html (Last access: February 21, 2020)
- 36) Alibaba global online trading website, http://www.alibaba.com/product-detail/Factory-supply-cheap-price-Caustic-soda_62389642400.html (Last access: February 21, 2020)
- 37) Alibaba global online trading website, http://www.alibaba.com/product-detail/price-of-solution-and-powder-chlorine_1852938369.html (Last access: February 21, 2020)
- 38) Indonesia drinking company website, <http://www.pamjaya.co.id/id/customer-info/drinking-water-tariff> (Last access: February 21, 2020)
- 39) Alibaba global online trading website, http://www.alibaba.com/product-detail/industrial-grade-sulfuric-acid-98-liquid_62345206005.html (Last access: February 21, 2020)
- 40) Alibaba global online trading website, http://www.alibaba.com/product-detail/Best-Price-98-Anthraquinone_60851738463.html (Last access: February 21, 2020)
- 41) Global petrol prices website, http://www.globalpetrolprices.com/Indonesia/electricity_prices/ (Last access: February 21, 2020)
- 42) Nordman, R.; Berntsson, T., *J Appl Therm Eng*, **26**, 363-373 (2006)
- 43) Commodity price indices website, <http://www.indexmundi.com/commodities/?commodity=wood-pulp&months=120> (Last access: February 21, 2020)
- 44) Alibaba global online trading website, http://www.alibaba.com/product-detail/High-Quality-Furfural-Furaldehyde-CAS-98_60835197916.html (Last access: February 21, 2020)
- 45) Sridach, W., *J Sci Technol*, **17**(2), 105-123 (2010)
- 46) Silva, J. F. L.; Selicani, M. A.; Junqueira, T. L.; Klein, B. C.; Vaz Júnior, S.; Bonomi, A., *Brazilian J Chem Eng*, **34**(3), 623-634 (2017)
-