Life Cycle Assessment for Integrated Dissolving Pulp and Furfural Production from Oil Palm Empty Fruit Bunch

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List of Abbreviations

EFB	*Empty Fruit Bunch*
CPO	*Crude Palm Oil*
PKO	*Palm Kernel Oil*
DP	*Dissolving Pulp*
ECF	*Elemental Chlorine-Free*
AQ	*Anthraquinone*
PHL	*Prehydrolysis Liquor*
TCF	*Totally Chlorine-Free*
P_{sa}	*Peroxymonosulfuric Acid*
IC	*Ion Chromatography*
AA	*Active Alkali*
PC	*Pulp Consistency*
HPLC	*High Performance Liquid Chromatography*
LCA	*Life Cycle Assessment*
cLCA	*consequential Life Cycle Assessment*
LCI	*Life Cycle Inventory*
CML	*Centrum voor Milieuwetenschappen Leiden (Institute of Environmental Sciences Leiden)*
GWP	*Global Warming Potential*
EP	*Eutrophication Potential*
AP	*Acidification Potential*
HTP	*Human Toxicity Potential*
CED	*Cumulative Energy Demand*
LCC	*Life Cycle Costing*

TEA	*Techno-Economic Assessment*

ABSTRACT

The oil palm empty fruit bunch (EFB) is the main biomass waste of the palm mill, but most of the waste is discarded at the plantation site without any value-added processing. The only existing commercial technology for EFB utilization is fertilizer production by the composting process. The abundance of cellulose and hemicellulose in the EFB can be converted into dissolving pulp and furfural. On the other hand, production of dissolving pulp is reliant on wood, which depletes forest resources. To prevent the over-exploitation of wood resources, a comprehensive approach is required considering non-wood material, such as EFB, for co-producing dissolving pulp and furfural accounting with environmental impacts.

Efforts have been done to utilize EFB for pulp production. The first EFB-based pulp mill was set up in East Malaysia (Sabah) in 2003. This mill conducted a soda cooking process to produce EFB pulp. The production of non-wood pulp, such as EFB pulp, has many advantages. The non-wood materials are more easily delignified than softwood, contain fine fibers that can be used for high-quality bleached pulp such as dissolving pulp, effective to substitute wood resources, and reduce the energy requirement for production.

In the Chapter 2, at laboratory scale, EFB-based dissolving pulp and furfural co-production experiment was done. The nitric acid prehydrolysis followed by soda cooking under atmospheric pressure was applied to the preparation of dissolving pulp. The furfural yield in the nitric acid prehydrolysate was increased to 6.2% of the EFB material weight by dehydration with an acid catalyst. The obtained pulp was then bleached by using peroxymonosulfuric acid

(P_{sa}), chlorine dioxide (D_0, D_1), and hydrogen peroxide (E_p) in the elemental chlorine-free (ECF) P_{sa}-D_0-E_p-D_1 sequence. The pulp demonstrated a brightness of 90.4% ISO and a viscosity of 6.5 cP, which met the National Standard of Indonesia, although the xylan content was a little high and the α-cellulose content was 83.0%.

In the Chapter 3, the consequential Life Cycle Assessment (cLCA) was developed to assess the environmental impact of EFB utilization for dissolving pulp production with furfural as a co-product. The inventory for the input-output materials including energy stream for the proposed integrated dissolving pulp and furfural production process was evaluated based on a previous bench-scale experiments. In the cLCA, the conventional dissolving pulp production process was considered to be replaced by a proposed process. In the existing condition, EFB was used for soil nutrients in the oil palm plantation. The EFB utilization shifting into dissolving pulp and furfural production will affect the total amount of chemical fertilizer in the oil palm plantation. The cLCA system boundary followed the system expansion from the forest or plantation to the end products of dissolving pulp and furfural. The SimaPro v8.0.5® software was used for the LCA calculation.

The baseline environmental impact categories, such as climate change or global warming potential (GWP100) in kg CO_2 eq unit, eutrophication potential (EP) in kg PO_4^{3-} eq unit, acidification potential (AP) in kg SO_2 eq unit, and human toxicity potential (HTP) in kg 1,4-dichlorobenzene eq unit, were quantified. The global warming potential is related to the 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. The emission characterization factor for climate change followed the characterization model as developed by the Intergovernmental Panel on Climate Change (IPCC). The eutrophication potential corresponds to the prediction for over-accumulation of nutrients. The characterization factor was based on the stoichiometric procedure of CML impact assessment method. The acidification potential corresponds to the prediction of the over-accumulation of acidifying substance in the environment. The characterization factor for acidifying substances to air was calculated based on the Regional Air Pollution Information and Simulation (RAINS) 10 model. Human toxicity potential is related to its effect on human health of toxic substances present in the environment. Its characterization factor was calculated based on the Uniform System for the Evaluation of Substance adapted for LCA purposes (USES-LCA).

This study examined three proposed scenarios for dissolving pulp production compared to the existing practice in Riau Province. In the conventional process, pulpwood is applied to prehydrolysis/ kraft cooking followed by ECF bleaching. In scenario 1, 50% of the wood consumption was replaced by EFB using acid prehydrolysis/ soda cooking followed by ECF bleaching, with an additional process to produce furfural. In scenario 2, 100% of wood consumption was replaced by EFB, with cooking and bleaching parameters being the same as scenario 1. In scenario 3, 100% of wood consumption was replaced by EFB, the acid prehydrolysis process was replaced by water prehydrolysis to improve the environmental performance. The scenario 3 was observed as the most promising scenario in this research and had the lowest environmental impact.

In the Chapter 4, the life cycle assessment (LCA), life cycle cost (LCC), and cumulative energy demand (CED) of the best scenario 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.

This research was conducted to propose EFB as the substitute of wood to produce dissolving pulp and furfural, which was considered to be environmentally sustainable and economically profitable. The scenarios were proposed and compared with the existing practice. The cLCA approach recommended that the EFB is a promising raw material referring to scenario 3 for integrated dissolving pulp and furfural production from the environmental point of view.

Keywords: *empty fruit bunch, dissolving pulp, furfural, life cycle assessment, life cycle costing, techno-economic assessment*

Chapter 1 General Introduction

1.1 Research background

Dissolving pulp that broadly called as viscose pulp, which is used as a raw material for manufacturing viscose staple fibers and high-grade specialty pulp. Viscose staple fibers are used for textile fiber market generally. Dissolving pulp can also be used as feedstock for cellulose products, such as cellophane, cellulose acetate, nitrocellulose, carboxymethyl cellulose, and cellulose ether [1,2]. The total production of dissolving pulp in the world was 8.5 million tons in 2017 [1]. The global dissolving pulp demand is predicted to expand in the next decades due to increasing of cellulose and textile fibers demand. The global production of textile fibers is predicted to increase to 133.5 million tons in 2030 by increasing in per capita consumption and population [3].

Currently, wood dissolving pulp is produced by the acid sulfite and prehydrolysis kraft processes since 1950s. A novel concept of dissolving pulp production regarding to its global demand increment is necessary to conduct. The efforts were done to improve dissolving pulp production based on productivity, sustainability, and environmental consideration point of view. Researchers suggested that non-wood materials can be used for dissolving pulp production due to deforestation and global warming issues.

The valorization of non-wood materials as dissolving pulp raw material allows wood raw materials to be saved for other use. It can also reduce wood fiber import in countries with a shortage of wood raw materials. The non-wood materials that potentially used for dissolving pulp raw material is agricultural crop wastes, such as sugarcane bagasse, bamboo, and palm oil empty fruit bunch (EFB).

As the largest palm oil exporter in the world, Indonesia has a huge amount of EFB that can be processed into valuable materials, such as dissolving pulp. The EFB is a rich carbon-source material that can be considered as a valuable material in the future. The utilization of EFB in pulp production began in 2003 when the first pulp mill using palm oil-based raw materials was set up in East Malaysia (Sabah) by the Forest Research Institute of Malaysia and Borneo Advanced Sdn. Bhd., a pulp and paper manufacturer [4], using a soda cooking process to produce EFB pulp.

In the dissolving pulp production, prehydrolysis process was necessary. During the prehydrolysis process, hemicelluloses and other organics are dissolved in the prehydrolysis liquor (PHL). In the dissolving pulp industry, this PHL was considered as a waste. The further processes to utilize this PHL into valuable products is needed. Furfural is a natural dehydration product of xylose, which is one of monosaccharide found in the hemicellulose fraction in the PHL.

The prehydrolysis/ soda-anthraquinone (AQ) cooking followed by elemental chlorine-free (ECF) bleaching process or nitric acid prehydrolysis/ soda cooking and the ECF bleaching can be used for co-producing dissolving pulp and furfural from EFB. As a proposed technology process, the feasibility assessment considers to environmental, energy, and economic approach is needed.

The Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Cumulative Energy Demand (CED) methodologies were needed to do due to evaluate the feasibility of the EFB as raw material for dissolving pulp and furfural co-production. LCA-LCC-CED comprehensively can give a precise interpretation for the company or decision-maker.

1.2 Problem statements

The problems stated in this dissertation are as follows:

1) The non-wood agricultural residue in Indonesia, such as EFB is potential to provide an alternative source of biomass for the dissolving pulp production.

2) Prehydrolysis process releases prehydrolysate that still contain large amounts of hemicellulose. This hemicellulose can be converted into valuable material, such as furfural.

3) Indonesia has sufficient amount of EFB that only used for composting process in the plantation area.

4) Feasibility study in the development of the EFB-based integrated dissolving pulp and furfural production is necessary.

1.3 Research objectives

The aim of the study was:

1) To prepare lab-scale co-production of dissolving pulp and furfural by nitric acid prehydrolysis/ soda cooking followed by ECF bleaching.

2) To simulate the mass balance of dissolving pulp and furfural co-production from the EFB.

3) To study the environmental impact of the EFB-based integrated dissolving pulp and furfural co-production by using Life Cycle Assessment (LCA) approach.

4) To evaluate EFB as a promising feedstock for dissolving pulp and furfural co-production in the environmental, energy usage, and economic parameters consideration.

Chapter 2 Production of Dissolving Pulp and Furfural as Biorefinery Products from Oil Palm Empty Fruit Bunch (EFB)

2.1 Introduction

Global vegetable oil production from oil palms (*Elaeis guineensis*) is dominated by Indonesia and Malaysia, with Indonesia producing 29 million metric tons of Crude Palm Oil (CPO) in 2014 [5]. Palm oil mills produce CPO and Palm Kernel Oil (PKO) as the main products, leaving residues such as shells, fibers, fronds, palm kernel cakes, and empty fruit bunch (EFB). However, most of these residues are not used, for example, EFB are the main by-product of palm fruit, but they are left rotting at the plantation site without further processing. It is known that EFB are lignocellulosic material, with an estimated cellulose content of 30-35%, while the hemicellulose and lignin contents are 15-35% and 20-30%, respectively [6]. The first oil palm-based pulp and paper mill was set up in Malaysia, and caustic soda technology is used for producing pulp [4]. The EFB can be utilized as a raw material for paperboard and medium density fiberboard [7].

Dissolving pulp (DP) is used as a raw material for manufacturing rayon and cellulose derivatives. The yield of an overall DP production process is 30-35%, which is relatively low when compared with regular paper pulp [8]. DP needs to be high quality, with a high degree of α-cellulose content, a low hemicellulose content, and an extremely low lignin content. Researchers have used lignocellulosic materials to produce DP. Andrade and Colodette produced DP from sugarcane bagasse using prehydrolysis soda cooking and elemental chlorine-free (ECF) bleaching [9]. Batalha et al. produced DP from bamboo using prehydrolysis soda-anthraquinone (AQ) cooking and chlorine or ECF bleaching sequences [10].

On the other hand, hemicelluloses are very useful in biorefinery processes, and can be released by prehydrolysis of lignocellulosic material at high temperature. Hemicelluloses in softwoods include arabinoglucoronoxylan, arabinogalactan, and galactoglucomannan, while the predominant hemicelluloses in hardwoods are glucuronoxylan and glucomannan [11], and it is interesting to compare these with other lignocellulosic materials. During the prehydrolysis stage of DP production, hemicelluloses and other organics are dissolved in the prehydrolysate liquor (PHL). The major reactions include depolymerization and dissolution of hemicelluloses [12,13], further degradation of pentose to products such as furfural and hydroxymethyl furfural [14], and acetic acid generation by the cleavage of acetyl groups, which is responsible for the decrease in pH during prehydrolysis [12,15].

Furfural is a natural dehydration product of xylose, which is mainly present as glucuronoxylan and glucuronoarabinoxylan. Furfural has been identified as one of the top thirty platform chemicals that could be made from biomass, along with two of its derivatives, furan dicarboxylic acid and levulinic acid [16]. Furfural is used as a selective solvent for separating saturated compounds from unsaturated compounds in petroleum refining, as well as for oil, gas, and diesel fuels, and there is high demand for its derivatives, particularly furfuryl alcohol, which is used as a precursor for furans resins [17]. Furfural has two important functional groups: an aldehyde and a conjugated system, which makes it a versatile compound for many applications. The furan ring system can undergo alkylation, hydrogenation, oxidation, halogenation, ring-opening reactions, and nitration [18,19].

In lignocellulosic materials, hemicellulose is easier to hydrolyze than cellulose. Thus, hemicellulose is selectively removed by an auto-hydrolysis. Unfortunately, auto-prehydrolysis is inefficient for extraction of xylan from hemicellulose in biorefineries. In order to enhance furfural production from the PHL, it is important to include a second-stage acid dehydration process. Lavarack et al. used hydrochloric and sulfuric acids to hydrolyze sugarcane bagasse hemicellulose [20]. Acid catalysis of EFB hydrolysis has been utilized to increase the sugar content in the hydrolysate [21].

Various acids including sulfuric, hydrochloric, hydrofluoric, nitric, and acetic acids are commonly applied as catalysts for hydrolysis processes. Rodriguez-Chong et al. used nitric acid to hydrolyze sugarcane bagasse to release large amount of sugars and produce degradation products, such as acetic acid and furfural [22]. Meanwhile, Ohi and Kishino studied on lignin degradation using nitric acid and nitrite [23]. Thus, in this study, nitric acid was also applied to the prehydrolysis process.

The aims of this Chapter were to clarify a method of preparing furfural and DP from EFB using prehydrolysis with nitric acid, and to determine how PHLs that contain xylan, and therefore nitric acid prehydrolysis was compared with auto-prehydrolysis to determine how the process produces a sufficient amount of furfural. Prehydrolysis and cooking conditions for preparation of unbleached EFB pulps were compared to understand how they affect pulp properties. In addition, ECF bleaching sequences using peroxymonosulfuric acid (P_{sa}) were studied to clarify their impact on the brightness and viscosity of the resulting DP.

2.2 Materials and methods

2.2.1 Materials

The EFB was obtained from the PT Perkebunan Nusantara VIII palm oil mill in Bogor, West Java, Indonesia. The EFB was cut into 10-15 cm fiber fragments and sun-dried to achieve 8-10% moisture content. The EFB fibers were then further cut to a length between 0.2 and 1 cm with a laboratory disk mill for the cooking process. The EFB materials were milled with a Willey mill and sieved to yield particle size of 40-80 mesh for chemical analysis. These samples were kept at room temperature and air-dried.

2.2.2 Nitric acid prehydrolysis soda cooking

The EFB materials (35 g, oven-dried) were placed in a 1 L glass reactor and subjected to prehydrolysis with 420 mL of nitric acid solution for 75 min at 96°C under atmospheric pressure. The dosage of HNO_3 was 32% based on EFB weight (oven-dried), and the ratio of liquor to EFB was 12 mL/g. After prehydrolysis, 100 mL of PHL and the residue (approximately 25 g, oven-dried) were separated. The residue was washed with water and subjected to soda cooking using a 20% dosage of active alkali (AA) for 3 h at 104°C under atmospheric pressure.

2.2.3 Auto-prehydrolysis soda-AQ cooking

The EFB materials (35 g, oven-dried) were placed in a 300 mL steel reactor and subjected to prehydrolysis with 245 mL of distilled water for 1-3 h at 150°C. After prehydrolysis, a portion (160 mL) of the PHL was removed. The liquor-to-solid ratio for the prehydrolysis step was 7 mL/g. After prehydrolysis, the wet solid residue was subjected to soda-AQ cooking for 3 h at 160°C using 20%

dosage of AA and 0.1% dosage of AQ, by adding the 1,4-dihydro-9,10-dihydroxyanthracene sodium salt (SAQ provided by Kawasaki Kasei Chemical Ltd.). The liquor-to-solid ratio for the soda-AQ cooking was 7 mL/g.

2.2.4 Chemical analysis

The acid-insoluble lignin (Klason lignin), acid-soluble lignin, extractive, and ash content of the materials and products were determined using TAPPI test methods T222 om-01, TAPPI UM 250, TAPPI T204 om-88, and T211 om-93, respectively. Sugar compositions were determined by ion chromatography (IC) of the filtrates of the acid hydrolysis, which had been diluted 1000 times, using a Dionex ICS 3000 system (Dionex, Sunnyvale, CA, USA) equipped with a single pump (SP-1), an electrochemical detector, an CarboPac PA 1 column, an CarboPac PA 1 guard column, and an auto sampler. The chemical composition of the nitric acid PHL was determined using part of the liquid that was neutralized by dropwise addition of 20% NaOH aqueous solution, followed by acid hydrolysis in 4% sulfuric acid at 121°C for 1 h. The kappa number, viscosity, and brightness of the pulps were determined using TAPPI test methods T236 om-13, T230 om-13, and T452 om-08, respectively. The brightness (% ISO) was measured using a Tokyo-Denshoku digital color meter (Model TC-3600).

After distillation of the PHL at 102°C, furfural was collected into the distillate and then analyzed using high performance liquid chromatography according to a previously reported method [24].

The nitrogen content of the residue after the nitric acid prehydrolysis was analyzed at the Chemical Analysis Division, Research Facility Center for Science and Technology, University of Tsukuba, Japan, using a Perkin-Elmer 2400 CHN elemental analyzer. The nitrate (NO_3^-) concentration in the nitric acid PHL and the distillate were determined by IC using an electric conductivity detector, an IonPac AS 12A column, and an IonPac AG 12A guard column.

2.2.5 Acid catalytic dehydration of prehydrolysis liquor (PHL)

As mentioned previously, EFB was prehydrolyzed with hot water for 1–3 h at 150°C. After this auto-prehydrolysis, PHL was subjected to acid catalytic dehydration by dropwise addition of 95% H_2SO_4 to reach a final sulfuric acid concentration of 2–6% after reaction for 1–2 h at 98°C under atmospheric pressure. After nitric acid prehydrolysis for 75 min, PHL was subjected to acid catalytic dehydration by dropwise addition of 95% H_2SO_4 to give a final sulfuric acid concentration of 2–6% after for 1 h at 98°C under atmospheric pressure.

2.2.6 Bleaching sequences and conditions

The resultant unbleached pulps were subjected to ECF bleaching using P_{sa}, chlorine dioxide (D_0, D_1), and alkaline peroxide (E_p) stages with a P_{sa}-D_0-E_p-D_1 sequence. The bleaching conditions are shown as follows:

P_{sa}: H_2SO_5 dosage: 0.2%, 1 h, 70°C, pH 3.0, pulp consistency (PC) 10%

D_0: ClO_2 dosage: kappa factor 0.30, 1 h, 70°C, pH 3.4, PC 10%

E_p: NaOH dosage: 1%, H_2O_2 dosage: 1.4%, 1 h, 70°C, PC 10%

D_1: ClO_2 dosage: 0.3%, 1 h, 70°C, PC 10%

Unbleached pulp (10 g, oven-dried weight) was first treated with a mixture of H_2SO_5, H_2SO_4, and H_2O_2 (0.19, 0.81, and 0.14 mmol/L, respectively) in a polyethylene bag. H_2SO_5 was synthesized by dropping 95% sulfuric acid (Wako Pure Chemical Industries, Ltd.) into 45% hydrogen peroxide aqueous solution (Mitsubishi Gas Chemical Company, Inc.) at 70°C, and a small amount of NaOH aqueous solution was added to the pulp at 10% PC to adjust the pulp suspension to pH 3.0 [25]. Then after washing, the pulp was treated with ClO_2 in a polyvinylidene chloride bag. After washing, the pulp was treated with NaOH and H_2O_2 in a polyethylene bag, washed again, and finally treated with ClO_2.

2.3 Results and discussion

2.3.1 Comparison of mass balance between nitric acid prehydrolysis and auto-prehydrolysis

Determination of the chemical composition of the EFB raw material is necessary to show the potential of using EFB in furfural and DP production. Table 2-1 shows that the EFB is a good candidate for biorefinery processes because of the high contents of glucan and xylan (31.1% and 16.5%, respectively). Xylan is an important source for production of xylose, which can be dehydrated further to furfural. Table 2-1 shows that xylan is the main component present in the nitric acid PHL (10.7%). Thus, the PHL is a potential source of xylan for furfural production.

This study also considered the important role of mass balance in describing the feasibility of prehydrolysis processes. The mass balance results show that the acid-insoluble lignin content of the residue from nitric acid prehydrolysis was lower than that of the residue from auto-prehydrolysis. In addition, the results show that the loss of acid-insoluble lignin (12.2%) during nitric acid prehydrolysis was higher than that during auto-prehydrolysis. The loss can be used to indicate the level of degradation of the acid-insoluble lignin component in the nitric acid treatment.

Table 2-1 Chemical composition of EFB raw material and PHL[a)]

	Acid-insoluble lignin (%)	Acid-soluble lignin (%)	Glucan (%)	Xylan (%)	Other sugars (%)	Extractive (%)	Ash (%)	Unknown (%)
EFB	28.0 ±0.4	3.0 ±0.2	31.1 ±2.4	17.5 ±1.6	0.8 ±0.1	8.6 ±1.1	5.5 ±0.2	5.5 ±3.0
Nitric acid prehydrolysis								
PHL	0.8 ±0.1	0.9 ±0.1	0.2 ±0.1	10.7 ±0.1	0.0 ±0.1	ND[a)]	ND	20.4±0.1
Residue [b)]	15.0 ±0.8	1.7 ±0.1	30.1 ±0.3	6.5 ±0.1	0.0 ±0.1	ND	ND	13.7±0.6
Loss	12.2 ±1.2	0.4 ±0.1	0.8 ±0.1	0.3 ±0.1	0.8 ±0.1	8.6 ±1.1	5.5 ±0.2	(-28.6 ±3.7)
Auto prehydrolysis								
PHL	1.5 ±0.2	1.6 ±0.2	0.2 ±0.1	1.7 ±0.1	0.5 ±0.1	ND [c)]	1.5 ±0.0	2.0 ±0.7
Residue [c)]	25.6 ±0.3	1.2 ±0.1	29.4 ±0.7	9.8 ±0.3	0.0 ±0.1	ND	ND	25.0 ±1.2
Loss	0.9 ±0.1	0.2 ±0.1	1.5 ±1.7	5.0 ±1.4	0.3 ±0.1	8.6 ±1.1	4.0 ±0.5	(-20.5 ±1.1)

a) Not determined

b) Yield: 67.1 ±0.1% of EFB material weight

c) Yield: 91.2 ±0.1% of EFB material weight

2.3.2 Effect of auto-prehydrolysis time on furfural production

The Table 2-2 shows that the xylan concentration increased with decreasing pH with prolonged auto-prehydrolysis time. This behavior can be assumed to lead to increased degradation of xylan to produce furfural. Fig. 2-1 shows that the prehydrolysis time affects the concentration of furfural in the auto-prehydrolysate (auto-PHL). After 3h of prehydrolysis, the furfural concentration increased from 3 to 17 ppm. However, the amount of furfural produced represents only 0.012% of the weight of the EFB material, therefore these conditions did not lead to efficient production of furfural.

Table 2-2 Carbohydrate composition of auto-PHL after various prehydrolysis times

Prehydrolysis time (h)	pH	Freeze-dried solid (%)	Glucan (%)	Xylan (%)	Others (%)
1	5.5 ±0.1	6.4 ±0.1	0.21 ±0.04	0.7 ±0.1	0.5 ±0.1
2	5.2 ±0.1	7.6 ±0.2	0.22±0.04	0.9 ±0.1	0.3 ±0.1
3	5.0 ±0.1	9.0 ±0.1	0.24±0.04	1.7 ±0.1	0.5 ±0.1

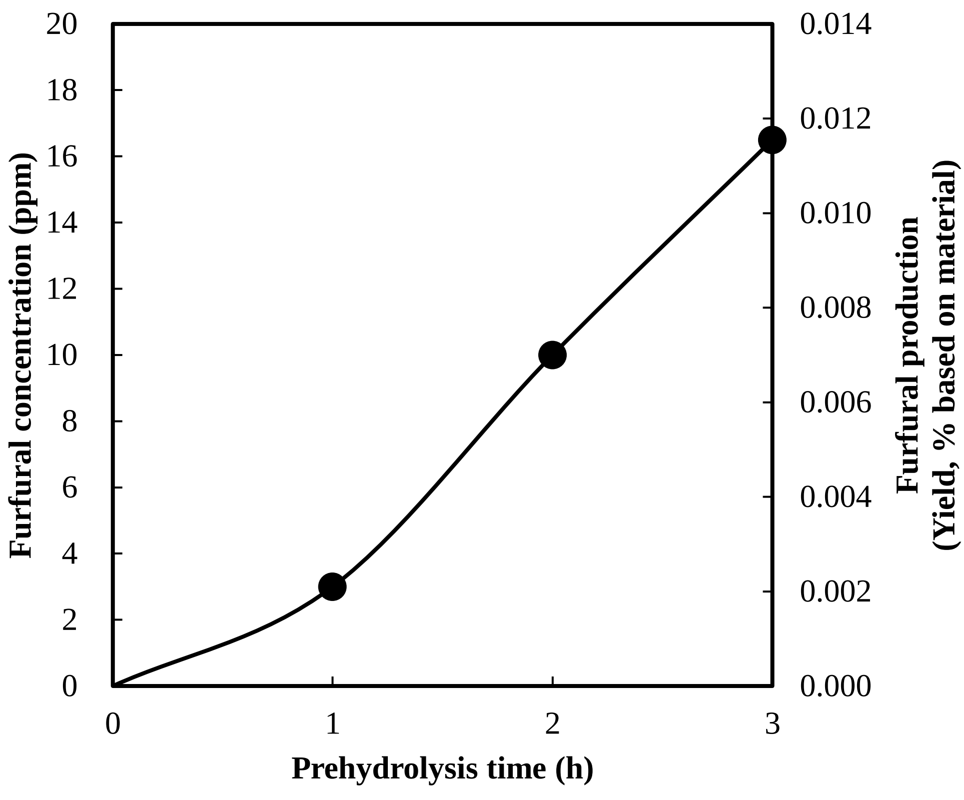


Fig. 2-1 Effect of prehydrolysis time on furfural production in the auto-PHL

2.3.3 Effect of sulfuric acid concentration on furfural dehydration in the auto-PHL

Conversion of xylose to furfural under acidic conditions using sulfuric acid follows the dehydration reaction mechanism shown in Fig. 2-2. This mechanism shows that a high concentration of an acid catalyst will be effective for furfural production until an optimum point is reached. As shown in Fig. 2-3, it was confirmed that by increasing the sulfuric acid concentration, the furfural concentration increased after the dehydration reaction. By using a dehydration reaction time of 2 h and a sulfuric acid concentration of 6% with the PHL, the furfural concentration in the product from the auto-PHL increased from 17 to 670 ppm. In this case, furfural production represented 0.47% of the EFB material weight.

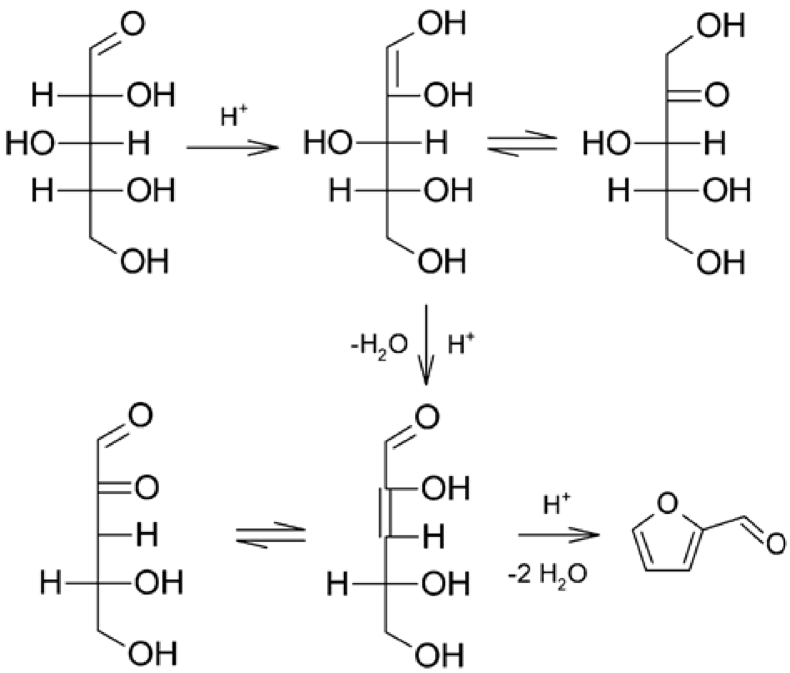


Fig. 2-2 Dehydration of xylose to furfural under acidic conditions

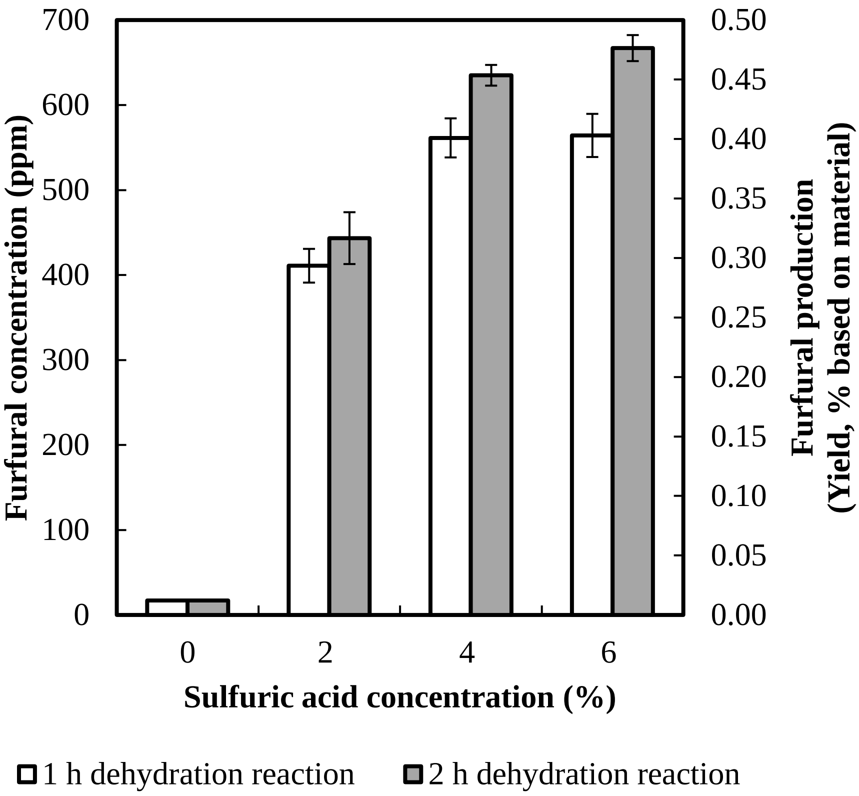


Fig. 2-3 Effect of sulfuric acid concentration on furfural production in the dehydration of auto-PHL

2.3.4 Effect of nitric acid prehydrolysis on furfural production from EFB

Next, utilization of a strong acid as a catalyst for furfural production was studied. By applying a nitric acid prehydrolysis method (2.7% of nitric acid concentration of the starting liquor: 32%÷12), the furfural yield reached 0.1% of the EFB raw material weight. The effect of sulfuric acid concentration during the 1 h dehydration reaction of the nitric acid PHL is shown in Fig. 3-4. Under these conditions, the furfural concentration increased from 98 to 5200 ppm, which means that the furfural yield increased to 6.2% of the EFB raw material weight.

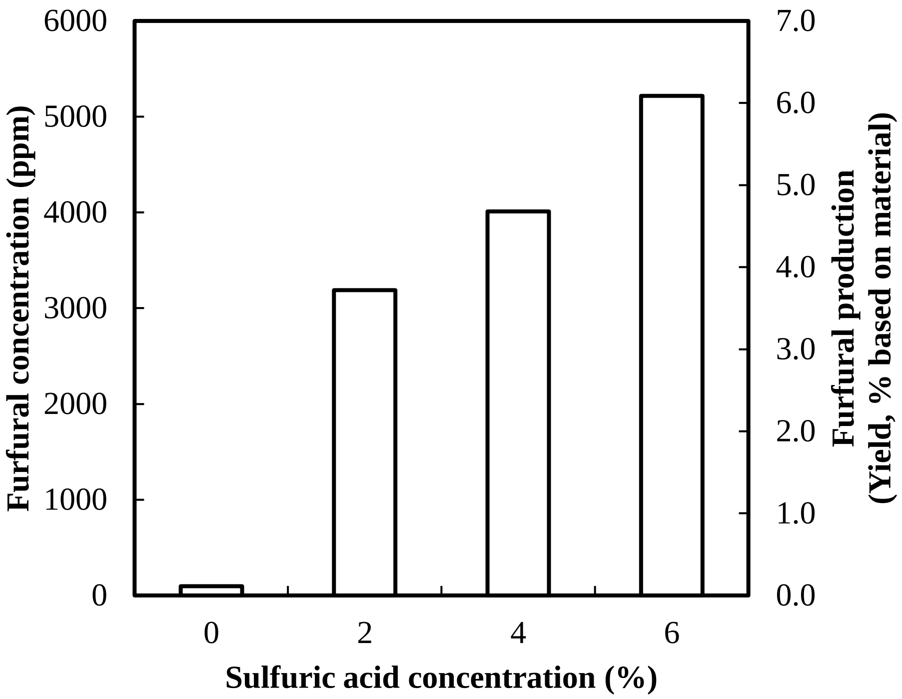


Fig. 2-4 Effect of sulfuric acid concentration on furfural production in the 1 h dehydration of nitric acid PHL

2.3.5 Preparation of Elemental Chlorine-Free (ECF) bleached pulp from nitric acid prehydrolysis soda pulp

Solid residue from the nitric acid prehydrolysis process was subjected to soda cooking under atmospheric pressure. The properties of the unbleached pulp were compared with those of the auto-prehydrolysis soda-AQ pulp (Table 2-3). The nitric acid prehydrolysis process provided a brighter unbleached pulp (58.3% ISO), but its viscosity was low (13.1 cP) when compared with that from the auto-prehydrolysis process. The kappa number of the unbleached pulp (6.8) was lower than that of the auto-prehydrolysis soda-AQ pulp (9.6). These differences could be due to nitric acid prehydrolysis assisting the degradation and dissolution of lignin during soda cooking.

Auto prehydrolysis followed by the soda cooking process has been proposed as a suitable method for the preparation of DP from EFB, and the optimum variables for soda cooking were statistically determined to be 161°C for 100 min with an alkali level of 26.1%, to attain a pulp with a screened yield of 31.2%, a kappa number of 6.0, and a viscosity of 16.1 cP [26]. AQ facilitates delignification under alkaline conditions, and improves yield and pulp properties [27,28]. In this study, auto-prehydrolysis for 3 h followed by soda-AQ cooking with a 20% AA dosage was selected as control conditions [29].

Nitric acid prehydrolysis soda pulp was subjected to the ECF bleaching sequence. The utilization of ECF bleaching instead of chlorine bleaching significantly lowers the quantity of organochlorine substances released in effluent streams. However, ECF bleaching still releases organochlorine compounds in the form of chloroform from bleaching and wastewater treatment processes. The partial substitution of chlorine dioxide in ECF bleaching with P_{sa} will eliminate adsorbable organic halogen (AOX) emissions in effluents and the amount of organochlorine substances found in the air [30]. P_{sa} treatment will also affect pulp quality by reducing the hexenuronic acid content, lowering the pulp kappa number, and reducing the lignin content, which are associated with acceptable pulp viscosity and brightness improvements [31,32].

The trends in viscosity loss and increases in brightness during the ECF bleaching sequence of the nitric acid prehydrolysis soda pulp are shown in Fig. 3-5. As shown in Table 3-4, the viscosity of the DP obtained from the nitric acid prehydrolysis soda pulp was 6.5 cP with a brightness of 90.4% ISO; thus, this bleached pulp met the National Standard of Indonesia [33]. However, as the pulp still contained 8.6% xylan, it is not suitable to be used as DP (usually <4.0% of xylan), and the bleaching conditions need to be further improved.

In a previous study [29], Harsono et al. reported that the α-cellulose content of the ECF-bleached pulp from auto-prehydrolysis soda-AQ pulp was 98.6%, which is inconsistent with the current results for nitric acid prehydrolysis soda pulp. The author used different methods to measure the qualities of the final products, with the glucan and xylan contents determined by IC in the current study and the weight of the α-cellulose content obtained by extraction with 17.5% NaOH in the previous work.

The α-cellulose of the EFB pulps in this study was lower than 98.6%, and this value reported in the previous study is incorrect. The author corrects an error in α-cellulose content in the previous study for the ECF-bleached pulp from the prehydrolysis soda-AQ pulp, which contained a similar amount of xylan to that from the nitric acid prehydrolysis soda pulp.

Table 2-3 Properties of unbleached pulps from nitric acid prehydrolysis soda cooking and auto-prehydrolysis soda-AQ cooking

	Cooking temp. (°C)	Pulp yield (%)	Kappa number	Brightness (% ISO)	Viscosity (cP)
Nitric acid hydrolysis soda pulp	104 ±2	34.3 ±0.1	6.8 ±0.1	58.3 ±0.4	13.1 ±0.3
Auto-prehydrolysis soda-AQ pulp	160 ±2	31.1 ±0.1	9.6 ±0.1	54.5 ±0.6	23.1 ±0.1

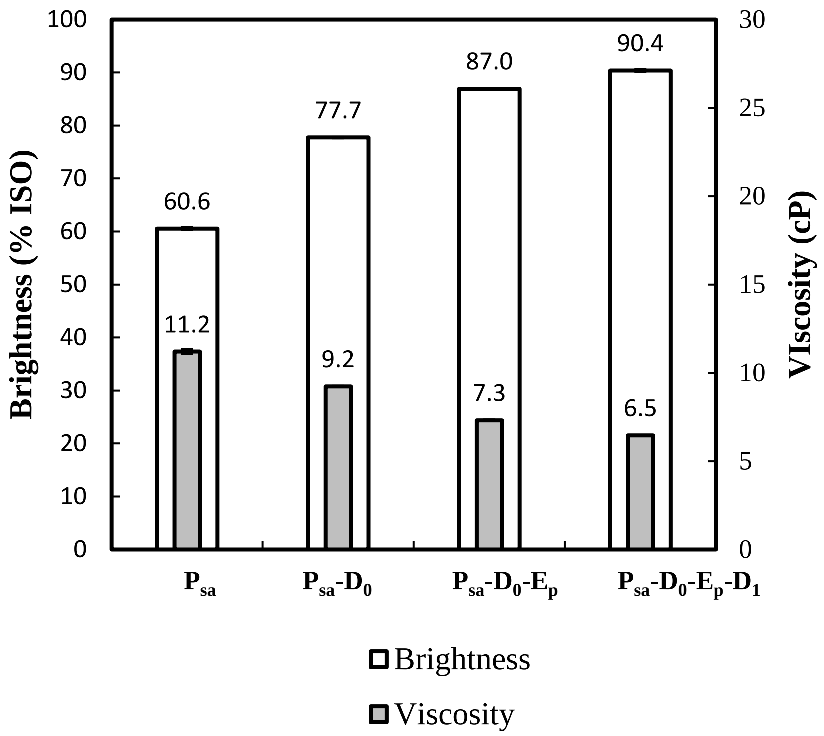


Fig. 2-5 Brightness and viscosity profile of nitric acid prehydrolysis soda pulp during P_{sa}-D_0-E_p-D_1 bleaching

Table 2-4 Properties of ECF-bleached pulp from nitric acid prehydrolysis soda cooking

Brightness (% ISO)	Viscosity (cP)	Ash (%)	α-Cellulose (%)	Glucan (%)	Xylan (%)
90.4 ±0.3	6.5 ±0.1	0.14 ±0.01	83.0 ±0.1	83.5 ±0.1	8.6 ±0.4

2.3.6 Dealing with waste nitric acid after prehydrolysis

In this study, the author tried to utilize the nitric acid liquor to produce furfural by a dehydration reaction. From the nitrogen content of the solid residue after nitric acid prehydrolysis (0.98% with a standard deviation of 0.01, we estimated the gaseous components of the vapor in the nitric acid reactor. There was approximately four times more dinitrogen monoxide (N_2O), which can be isolated and used for other purposes, than the sum of NO and NO_2. In addition, CO and CO_2 were detected. Based on the analysis of nitrate (NO_3^-) in the nitric acid PHL we can assume a nitrogen balance for the process, as shown in **Fig. 3-6**. As a next step in this project, the author believes that the processes should be developed to recover and reuse the majority of nitric acid used in this process.

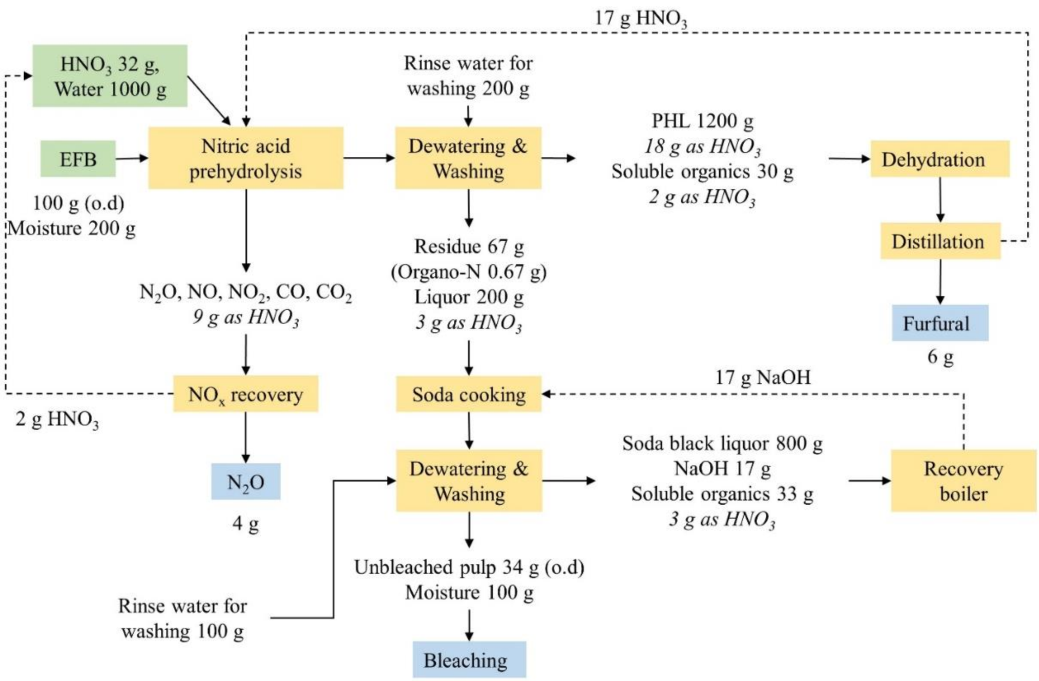


Fig. 2-6 Nitric acid balance of the proposed process and how to deal with the nitric acid PHL

2.4 Conclusions

As a bio-refinement method for oil palm EFB, nitric acid prehydrolysis soda cooking demonstrated that a furfural yield from the PHL was 6.2% of EFB material weight. The pulp demonstrated a brightness of 90.4% ISO and a viscosity of 6.5 cP, which were acceptable according to the Indonesian National Standard after ECF bleaching with P_{sa}-D_0-E_p-D_1 sequence using peroxymonosulfuric acid, chlorine dioxide, and hydrogen peroxide.

Chapter 3 A Consequential Life Cycle Assessment (LCA) Approach in the Development of Integrated Oil Palm Empty Fruit Bunch (EFB)-based Dissolving Pulp and Furfural Production

3.1 Introduction

In the previous Chapter, dissolving pulp and furfural successfully produced from oil palm empty fruit bunch (EFB) in the laboratory scale. The feasibility of the EFB utilization to substitute the conventional process of dissolving pulp and furfural production was necessary. In this Chapter, the proposed processes of integrated dissolving pulp and furfural feasibility study was done through environmental consideration.

Production of dissolving pulp mostly depends on wood, which depletes forest resources drastically. To prevent the exploitation of wood resources, a comprehensive approach is required considering waste materials for co-producing dissolving pulp and furfural accounting with environmental impacts. Palm oil mills produce biomass wastes such as empty fruit bunch (EFB), oil palm fronds, oil palm trunks, palm kernel shells, and palm mesocarp fibers. Pulp production can be replaced with waste-based material such as EFB from oil palm mills. EFB is the main biomass product of the palm mill, but most of the waste is discarded at the plantation site without any value-added processing.

Several technologies are being developed for EFB utilization, but the only existing commercial technology is fertilizer production by the composting process [34,35,36,37]. Meanwhile, the development of biorefinery products from EFB is promising. The chemical composition of EFB consists mostly of cellulose, hemicellulose, and lignin, shown in comparison with the composition of wood material in Table 3-1. Each of these chemical components from EFB can be used to produce valuable products. A description of the biorefinery products derived from EFB is described in Fig. 3-1.

Table 3-1 Chemical characterization of EFB compare to wood

Material		Lignin (%)	Cellulose (%)	Hemicellulose (%)	Extractive (%)	Ash (%)	Unknown (%)
EFB		31.0	31.1	17.5	8.6	5.5	6.3
Wood[38]	*E. globulus*	27.6	49.4	15.3	0.6	-	7.1
	A. mearnsii	24.5	49.2	19.3	1.2	-	5.8
	*A. hybrid**	30.3	49.2	13.8	1.5	-	5.2

* *A. mangium and auriculiformis*

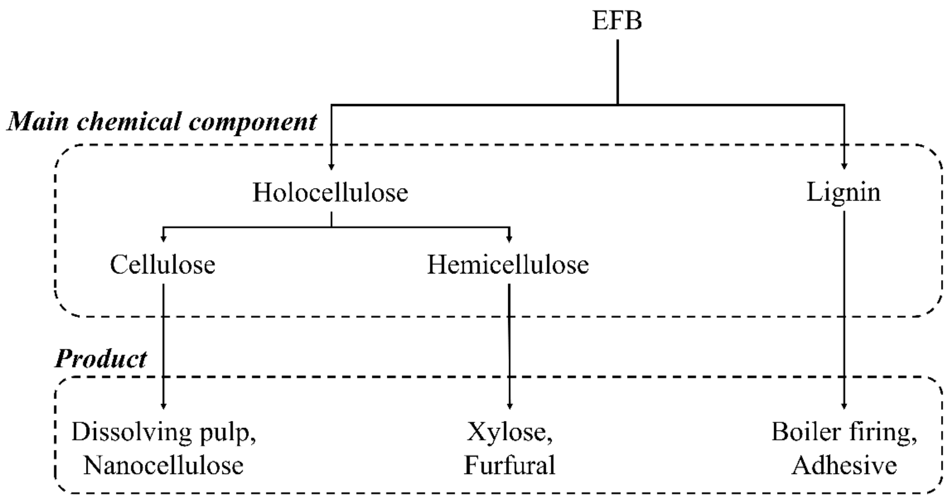


Fig. 3-1 Potential biorefinery products from EFB based on its chemical component

Utilization of EFB in pulp production began in 2003 when the first pulp mill using palm oil-based raw materials was set up in East Malaysia (Sabah) by the Forest Research Institute of Malaysia and Borneo Advanced Sdn. Bhd., a pulp and paper manufacturer [4], using a soda cooking process to produce EFB pulp. Sharma et al. later produced EFB pulp in a soda-anthraquinone (AQ) pilot-scale plant for ECF bleaching [39]. The production of pulp from non-wood materials such as EFB has many advantages. Non-wood materials are more easily delignified than softwood, contain fine fibers that can be used for high-quality bleached pulp like dissolving pulp, effective to substitute wood resources, and reduce the energy requirement for production [40].

Dissolving pulp is a raw material for cellulosic fibers (rayon and acetate), used as an alternative to cotton, specialty papers (photographic papers, filters), and viscose clothing and hygiene products [41]. Generally, in high-grade dissolving pulp products, a purification method, such as prehydrolysis [11], pre-alkaline extraction [42], hot caustic extraction, and cold caustic extraction [43], are necessary.

Currently, the fresh pulp for dissolving pulp production is only derived from wood raw materials, and the wood dissolving pulp industry is far more established than the non-wood dissolving pulp industry [44]. Generally, the production of dissolving pulp from wood uses acid sulfite cooking or prehydrolysis/ kraft cooking process. Because non-wood biomass is one of renewable resources, non-wood biomass is potentially becoming a complement to wood as raw material, minimizing the environmental impact, increasing sustainability, and reducing the pressure on industrial forestry.

Global dissolving pulp capacity was 7.6 million tons at the end of 2017 [45]. The top six producers, including Sappi, Aditya Birla, Lenzing, Sun Paper, Bracell, and Rayonier produce 55.5% of the global production. In Indonesia, PT Asia Pacific Rayon located at the Riau province, which is expected to be the largest dissolving pulp manufacturer in Indonesia, started manufacturing dissolving pulp with a production capacity of 350,000 tons per year [46]. The second-largest manufacturer in Indonesia is PT Toba Pulp Lestari, located at the North Sumatra Province with a 240,000 tons per year production capacity [47].

Several researchers have had an interest in the development of dissolving pulp from non-wood materials. The dissolving pulp was produced from sugarcane bagasse and bamboo by using prehydrolysis/ soda cooking and ECF bleaching process [9,10]. It also can be produced from the banana stem by using three kinds of cooking processes (kraft, alkaline sulfite-AQ, and soda-AQ) [48]. These products were also processed by prehydrolysis before cooking, followed by the ECF bleaching process. The dissolving pulp from EFB was produced using the prehydrolysis/ soda-AQ cooking and the ECF bleaching process [29]. Integrated dissolving pulp and furfural were produced using nitric acid prehydrolysis/ soda cooking and the ECF bleaching process in the Chapter 2. However, these researches reported only the process of pulp production without refereeing environmental impact due to uses of *waste-to-product* on large scale.

Producing integrated dissolving pulp and other biorefinery products increase environmental performance because of the utilization of waste in the process as raw material. A potential product, furfural can also be integrated into the dissolving pulp production process. Furfural is a selective solvent used for separating saturated compounds from unsaturated compounds in petroleum refining, oil, gas, and diesel fuel. It is in high demand because of its derivatives, particularly furfuryl alcohol, which is used as a precursor for furan resin [17,49]. Furfural is produced from a prehydrolysis liquor that still contains a large amount of hemicellulose. Fig. 3-2 describes the derivation and utilization of furfural in the industry. Researchers have studied the production of furfural from the prehydrolysis liquor of dissolving pulp production process from conventional wood sources [11,50,51].

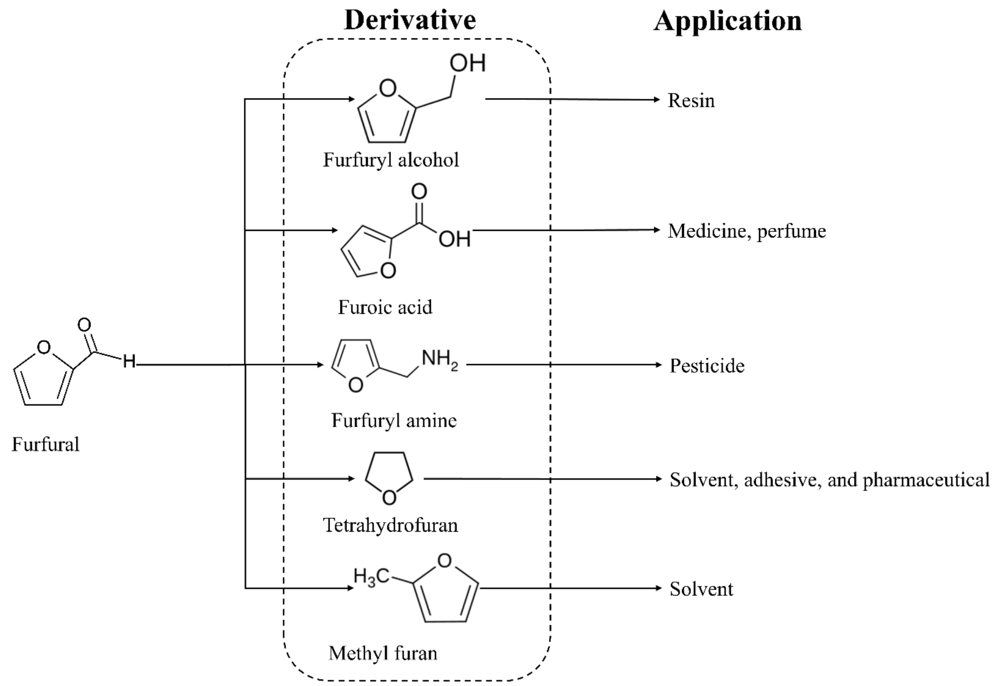


Fig. 3-2 Furfural derivatives and their application in the industry

There is a significant potential to utilize EFB waste to produce furfural without competing natural wood sources. In this regard, consequential LCA (cLCA) has the merit to analyze the production capability of furfural from EFB and environmental impacts.

LCA has received research attention in the last few years [52,53]. Researchers have included LCA in their feasibility studies for pulp production from wood sources [41,54,55,56,57]. There are two approaches in the LCA study, attributional LCA (aLCA) and cLCA. The aLCA provides information focused on the relevant physical flows to and from a product's life cycle system. The system investigated is limited to a single full life cycle from *cradle-to-grave* [58]. The cLCA describes the consequences of changes in the level of output (and consumption and disposal) of a product, including effects both on the inside and outside of the product's life cycle [59,60]. In our best knowledge, there are no researches were taken the LCA approach for EFB, which has significant importance to produce dissolving pulp and furfural. Thus, it is necessary to include the LCA perspective in EFB utilization for integrated dissolving pulp and furfural production to understand the environmental impacts with indicators of global warming potential, acidification potential, eutrophication potential and human toxicity potential due to uses of EFB waste. Therefore, the purpose of this Chapter is to assess the environmental impacts of dissolving pulp production processes from EFB using LCA methodology to report the indicators. It was beneficial to prove EFB as an alternative raw material for the dissolving pulp industry.

3.2 Materials and methods

3.2.1 Material and location for cLCA model

In the proposed scenario, EFB was used as a raw material to substitute wood in the production of dissolving pulp and furfural as co-product. The current leading dissolving pulp industry in Indonesia is in Riau Province, which also had the largest oil palm plantation in Indonesia with a total area of 2.4 million hectares [61]. The most productive area in Indonesia was distributed throughout Sumatra and Kalimantan (Fig. 3-3, [61]). The proximity of the raw material supplier and dissolving pulp mill location in the same province was advantageous for the use of EFB as a resource in dissolving pulp production in Indonesia.

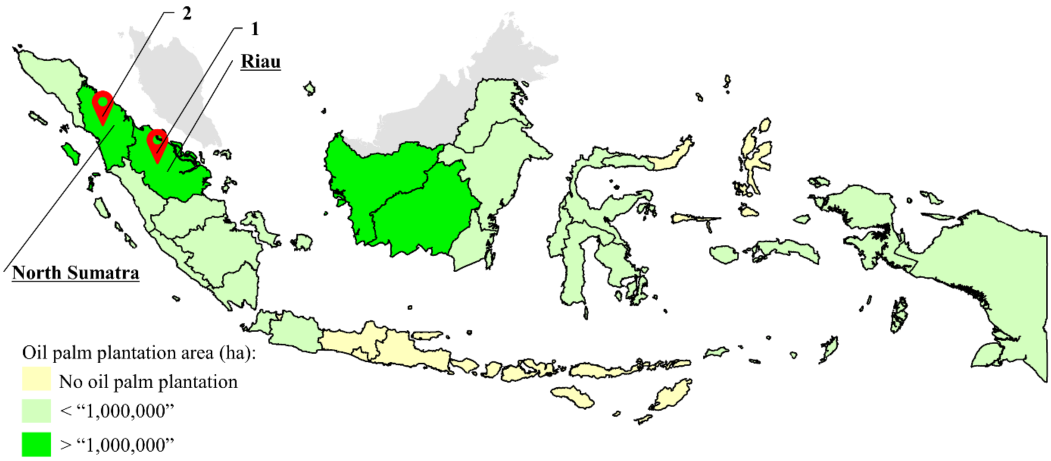


Fig. 3-3 Oil palm plantation distribution areas and dissolving pulp industry location in Indonesia [62]

1: Dissolving pulp mill in Riau Province (capacity 350,000 t/y),

2: Dissolving pulp mill in North Sumatra Province (capacity 240,000 t/y)

3.2.2 Goal and scope

The goal of this study is to quantify the environmental impact of three scenarios for dissolving pulp production compared to the existing practice in Riau Province. In the Scenario 1, 50% of the wood consumption was replaced by EFB using acid prehydrolysis/soda cooking followed by ECF bleaching, with an additional system process to co-produce furfural. In the Scenario 2, 100% of wood consumption was replaced by EFB, with cooking and bleaching parameters are the same as those in the Scenario 1. In the Scenario 3, 100% of wood consumption was replaced by EFB and the acid prehydrolysis was replaced by water prehydrolysis to improve the total environmental performance with the same cooking and bleaching conditions as the previous scenarios. The consequential approach followed the system expansion from the forest or plantation to the final co-products of the dissolving pulp and furfural was used in this LCA study.

3.2.3 Basis for inventory data collection

The field survey was conducted in the dissolving pulp mill in Riau Province in order to collect the key information related to the production of dissolving pulp from wood chips and to confirm the feasibility of EFB-based dissolving pulp in the large-scale production. The operational parameters related to direct input-output inventory analysis in this conventional dissolving pulp mill, such as pulp yield, chemical dosage, prehydrolysis, cooking, and bleaching processes, were observed and used in the inventory analysis.

In this study, the commercial dissolving pulp yield based on wood chips raw material was 40%. The chemicals used to produce dissolving pulp were sodium hydroxide, sodium sulfide, chlorine dioxide, and hydrogen peroxide. The three main processes in the conventional production of dissolving pulp were prehydrolysis, kraft cooking, and ECF bleaching. The water was the only input material in the prehydrolysis process. However, the cooking and bleaching processes consumed large amounts of chemicals. In this process production, the prehydrolysis liquor was discarded without any value-adding process.

In the proposed scenario, the dissolving pulp was produced from EFB by following the key data obtained in the laboratory-scale experiment. This method was conducted because an EFB-based commercial-scale dissolving pulp production has not been established yet. The engineering approach in the inventory analysis for the LCA calculation was conducted for the proposed large-scale development. Based on the data obtained in the laboratory-scale experiment, the dissolving pulp yield of 34% based on EFB raw material was slightly lower than that of the wood-based process. In the case of EFB raw material, the milder process condition can be applied to produce dissolving pulp. The EFB-based dissolving pulp production process was divided into two pathways in this study. The first pathway, used in the Scenario 1 and 2, consisted of acid prehydrolysis, soda cooking, and ECF bleaching processes. The process of acid prehydrolysis used 32% of nitric acid consumption based on EFB weight to increase the degradation of hemicellulose into xylose, which was important to obtain more furfural. The second pathway, used in the Scenario 3, consisted of prehydrolysis, soda-AQ cooking, and ECF bleaching. The details of all the processes in this study are described in Table 3-2.

Table 3-2 Technical data of process conditions for direct inputs and outputs

Process stage	Process condition
Prehydrolysis	
Prehydrolysis (for wood)	Water to wood ratio: 4; T: 150 °C; t: 180 min
Prehydrolysis (for EFB)	Water to EFB ratio: 7; T: 150 °C; t: 180 min
Acid prehydrolysis	Water to EFB ratio: 12; T: 96 °C; t: 75 min; HNO_3 dosage: 32% based on EFB
Cooking	
Kraft	Water to wood ratio: 4; T: 150 °C; t: 180 min; AA: 18% based on wood; sulfidity: 30%
Soda	Water to EFB ratio: 7; T: 104 °C; t: 180 min; AA: 20% based on EFB
Soda-AQ	Water to EFB ratio: 7; T: 160 °C; t: 180 min; AA: 20% based on EFB; AQ dosage: 0.1% based on EFB
ECF bleaching	
P_{sa}	H_2SO_5 dosage*: 0.2% based on pulp; T: 70 °C; t: 60 min; PC: 10%
D_0	kappa factor: 0.30; T: 70 °C; t: 60 min; PC: 10%
E_p	NaOH dosage: 1% based on pulp; H_2O_2 dosage: 1.4%; T: 70 °C; t: 60 min; PC: 10%
D_1	ClO_2 dosage: 0.3% based on pulp; T: 70 °C; t: 60 min; PC: 10%

P_{sa}: Peroxymonosulfuric acid bleaching
D_0: First chlorine dioxide bleaching
E_p: Alkaline peroxide bleaching
D_1: Second chlorine dioxide bleaching
AQ: Anthraquinone
AA: Active alkali
PC: Pulp consistency
***** H_2SO_5 was synthesized from H_2O_2 and H_2SO_4

3.2.4 Life cycle inventory (LCI) analysis

In this study, the cLCA was performed by following the ISO 14040 methodology to evaluate the comparison of environmental performance of EFB-based and wood-based dissolving pulp productions. Input-output inventory related to direct EFB dissolving pulp production (foreground process) was based on bench-scale experimental data in the Chapter 2, the previous publication [29] and literature review [54,62]. EcoInvent and Agri-footprint databases have been used for the background data system inventory in the LCA calculation. Input-output inventories for direct energy and materials used in all production processes have been described in Table 3-3.

Table 3-3 Direct inputs and outputs of 1 kg dissolving pulp production from wood and EFB raw material

	Unit	Wood (PH-K-ECF)	EFB (APH-S-ECF)	EFB (PH-S-ECF)
Input				
Material				
Pulpwood, 50 % M.C	kg	4.500	-	-
EFB, 50 % M.C	kg	-	5.294	5.294
Na_2S	kg	0.153	-	-
H_2O_2	kg	0.013	0.013	0.013
NaOH for cooking	kg	0.366	0.683	0.683
NaOH for bleaching	kg	0.009	0.009	0.009
Chlorine dioxide	kg	0.032	0.032	0.031
HNO_3	kg	-	0.847	-
Water	m^3	0.045	0.086	0.073
Sulfuric acid	kg	-	1.906	1.112
Anthraquinone	kg	-	-	0.003
Urea (as consequential effect)	kg	-	0.016	0.016
Energy				
Electricity	kWh	0.433	0.408	0.443
Steam	kWh	3.083	1.750	2.222
Transportation				
Truck	t km	0.225	0.265	0.265
Output				
Dissolving pulp (a.d)	kg	1.000	1.000	1.000
Furfural	kg	-	0.159	0.011
N_2O (by-product)	kg	-	0.106	-
Black liquor (waste)	kg	Recovered	18.529	18.529
Emission				
CO_2 fossil	kg	0.100	-	-
CO_2 biogenic	kg	2.690	0.079	0.079
NO_x	kg	0.002	Recovered	-

M.C: Moisture Content; a.d: air dried; PH-K-ECF: Prehydrolysis/ kraft cooking followed by ECF bleaching; APH-S-ECF: Acid prehydrolysis/ soda cooking followed by ECF bleaching; PH-S-ECF: Water prehydrolysis/ soda-AQ cooking followed by ECF bleaching

3.2.5 Consequential approach

Fig. 3-4 shows a system boundary of the cLCA approach for the proposed integrated dissolving pulp and furfural production from EFB. This conventional dissolving pulp production process was assumed to be replaced by a proposed process. In the existing condition, EFB was used for soil nutrients in the oil palm plantation. The EFB utilization shifting into dissolving pulp and furfural production will affect the total amount of chemical fertilizer. Oil palm plantation in Indonesia mostly still used chemical fertilizer as a major source of nutrients. The environmental impact of all system process (investigated and substitute process) was quantified.

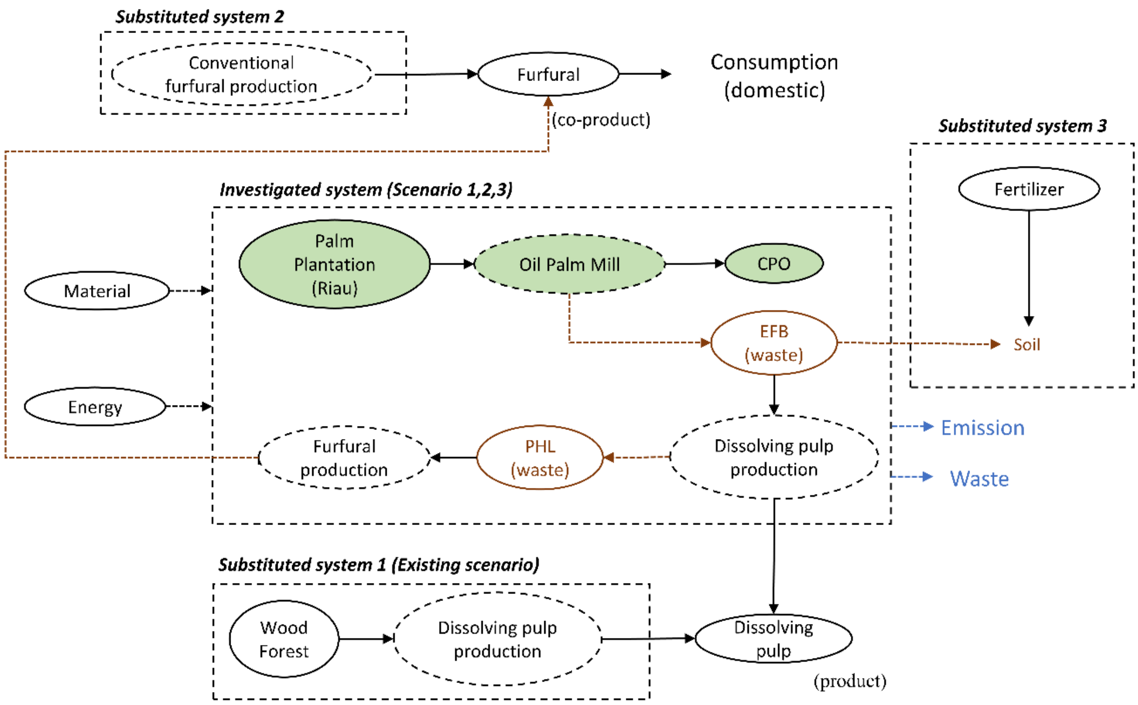


Fig. 3-4 Consequential approach system boundary in the proposed dissolving pulp and furfural production scenario

3.2.6 Environmental impact analysis

Several environmental impact categories have been quantified, such as Acidification Potential (AP), Global Warming Potential (GWP100), Eutrophication Potential (EP), and Human Toxicity Potential (HTP). AP, expressed as kg SO_2 equivalent, includes acidification due to fertilizer use, according to the method developed by the Intergovernmental Panel on Climate Change (IPCC). Climate change caused by greenhouse gases is represented by GWP, measured in kg CO_2 equivalent. This parameter is frequently expressed over various time spans, with the most common being the GWP100 (100 years). Eutrophication is the over-accumulation of nutrients in aquatic systems. It is indicated by the increment of nitrogen and phosphorus concentrations and is expressed as kg N equivalent and kg PO_4^{3-} equivalent, respectively. Human toxicity is the toxic effects that chemicals have on humans. Generally, it is expressed as kg 1,4-DB equivalent [63,64,65]. The software used for the environmental impact analysis in this study was SimaPro v8.0.5® from Pré-sustainability with *Centrum voor Milieuwetenschappen Leiden* (CML) as an environmental impact assessment method. cLCA calculation was conducted using the following equation.

$$Environmental\ Impact = \Sigma\,\{(E_p \times f_{substance}) - (E_s \times f_{substance})\} \qquad (3\text{-}1)$$

Here, E_p is the emission through identified product chain (kg/kg functional unit), E_s is the emission from substituted product chain (kg/kg functional unit) and $f_{substance}$ is the characterization factor for each emission.

3.2.7 Limitation of LCA study

Because most of the proposed scenarios inventory data originate from lab-scale experiments, the various parameters for scaling-up to the industrial scale alters the result of environmental impact. The sensitivity analysis was performed for the electricity and steam inputs for the proposed scenarios in the range of 10% above and below of the base value to show the effect of the difference in steam and electricity inputs on the alteration of the total cLCA result. The replacement of wood-based feedstock by EFB-based feedstock is still in the initial phase, so the EFB-based dissolving pulp production using the soda pulping process still has opportunities for improvement.

3.3 Results and discussion

3.3.1 Environmental impact assessment for the existing condition of dissolving pulp production from wood

The environmental impact of the existing process of dissolving pulp production from wood raw material was studied for Riau Province. In Fig. 3-5, the existing conditions of EFB and dissolving pulp production were simulated based on the field observations, laboratory inventory datasets and literatures. Dissolving pulp production capacity in Riau Province is 350,000 tons per year which requires 35,118 ha of wood forest. This scenario shows environmental impact of 9.16×10^8 kg CO_2 eq of GWP100, 5.75×10^6 kg SO_2 eq of AP, 1.50×10^6 kg PO_4^{3-} eq of EP, and 2.66×10^8 kg 1,4-DB eq of HTP per year. Riau Province produces 8.9 million tons per year of EFB that potentially could be used for dissolving pulp production. Currently, EFB is discarded without any further processing.

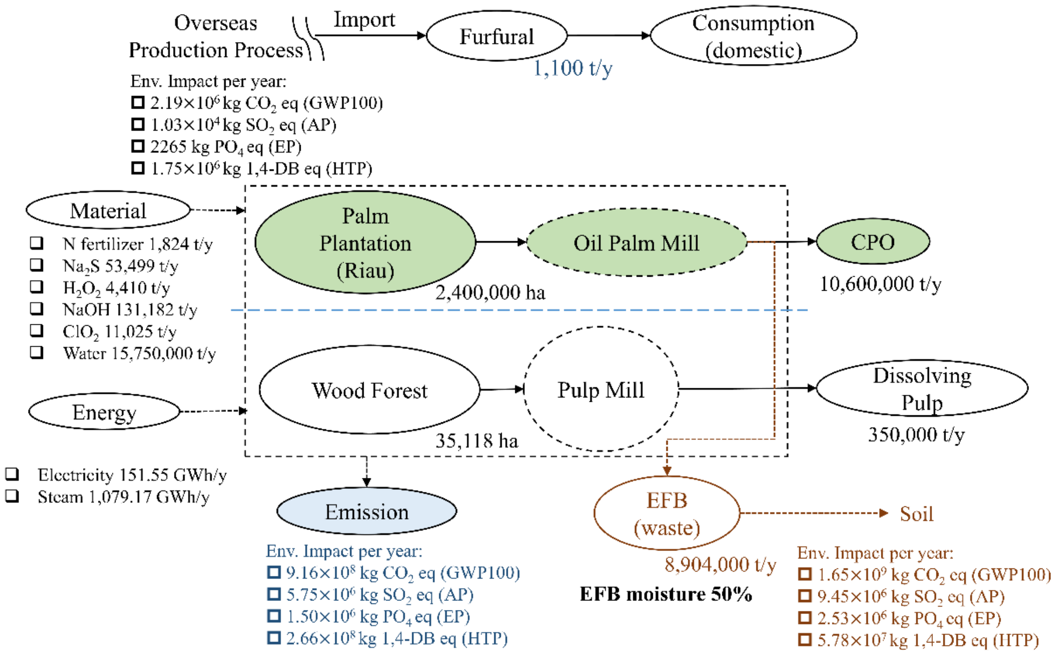


Fig. 3-5 LCI analysis and environmental impact assessment for palm oil existing condition and prehydrolysis/ kraft cooking process for dissolving pulp production in Riau Province

Furthermore, EFB utilization for biomass valorization purposes, such as dissolving pulp production, is promising in the near future. The sulfur-free pulping system using a soda process can be applied for EFB delignification. One advantage of using a non-wood raw material such as EFB is that this material is easier to delignify than wood. A prehydrolysis process is necessary for eliminating hemicellulose. An excessive amount of hemicellulose, particularly xylan, can cause poor filterability of viscose and discoloration of viscose products [66,67]. On using acid prehydrolysis, more hemicellulose is degraded and dissolved into the liquor. A sufficient amount of xylose and xylo-oligomer in the prehydrolysis liquor can be used for producing furfural as a co-product. Currently, Indonesia imports 1,100 tons per year of furfural for various purposes.

The main direct material inputs for producing dissolving pulp from wood are water, sodium hydroxide, hydrogen peroxide, and chlorine dioxide. Table 4-2 shows the input-output inventories of direct materials and energy for dissolving pulp production.

3.3.2 Environmental impact assessment for proposed integrated process for dissolving pulp and furfural production

In the cLCA approach, the utilization of EFB waste to produce dissolving pulp affects the consumption of wood for producing dissolving pulp. This consequence was assumed as compensation for dissolving pulp production using EFB. Additionally, the co-production of furfural has the benefit of being a substitute material for commercial furfural. The simulations of EFB utilization for dissolving pulp and furfural production are shown in Figs. 3-6 and 3-7.

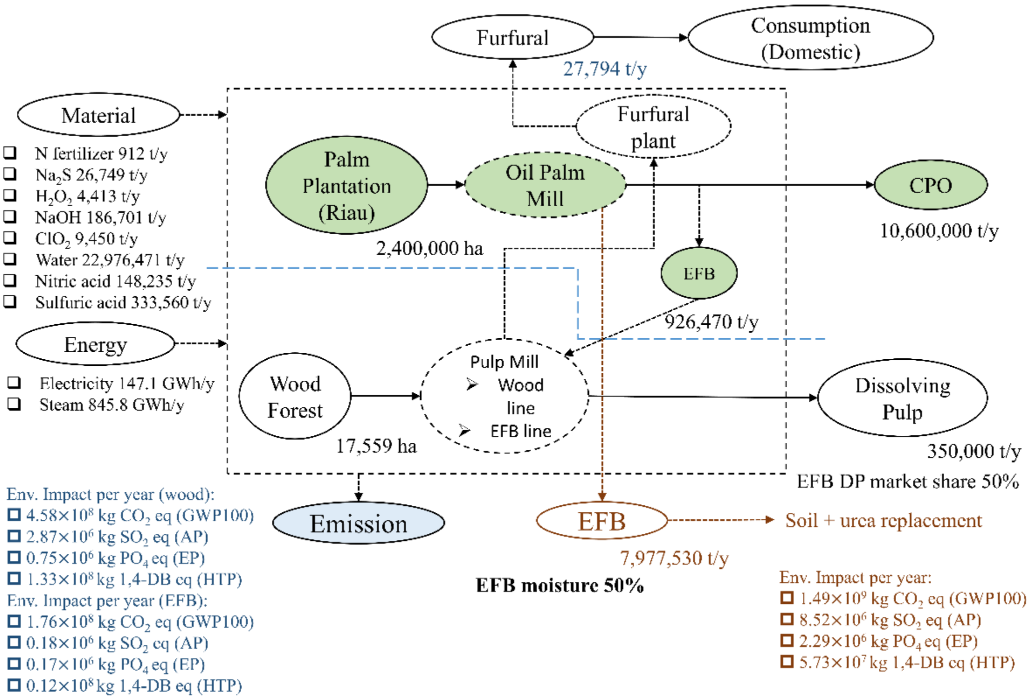


Fig. 3-6 LCI analysis and environmental impact assessment for 50% of wood replaced by EFB with acid prehydrolysis/ soda cooking for dissolving pulp production (Scenario 1)

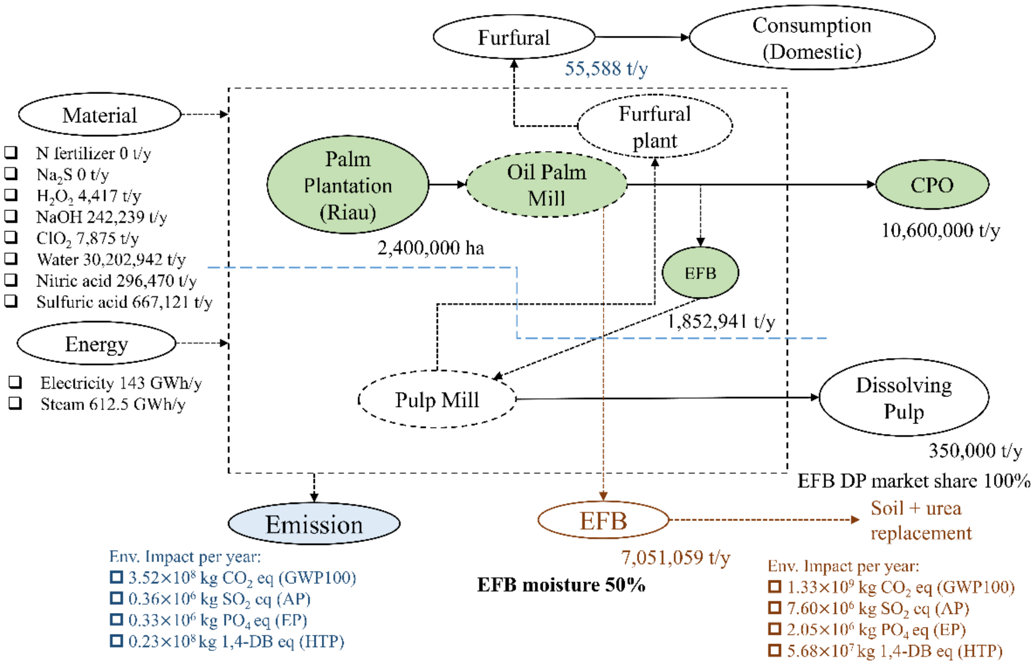


Fig. 3-7 LCI analysis and environmental impact assessment for the 100% of wood replaced by EFB with acid prehydrolysis/ soda cooking for dissolving pulp production (Scenario 2)

This proposed process can reduce environmental impact. In the existing condition, for producing 1 kg of dissolving pulp turned out 0.0164 kg SO_2 eq of AP, 2.62 kg CO_2 eq of GWP100, 0.0043 kg PO_4^{3-} eq of EP, and 0.760 kg 1,4-DB eq of HTP. In the consequential approach, by using the proposed Scenarios 1 and 2, AP decreased to 0.0087 kg SO_2 eq and 0.0010 kg SO_2 eq, respectively; GWP100 decreased to 1.81 kg CO_2 eq and 1.01 kg CO_2 eq, respectively; EP decreased to 0.0026 kg PO_4^{3-} eq and 0.0009 kg PO_4^{3-} eq, respectively; HTP decreased to 0.41 kg 1,4-DB eq and 0.07 kg 1,4-DB eq, respectively. Fig. 3-9 shows the environmental impact analysis results for each scenario based on 1 kg of dissolving pulp product as the functional unit.

This proposed process has another advantage in the case of furfural co-production that can potentially satisfy the furfural demand in Indonesia. If furfural demand is covered by the co-production process, the environmental impact caused by imported furfural could be eliminated, as shown in Figs. 3-6 and 3-7. However, these proposed processes (Scenarios 1 and 2) decreased the dissolving pulp quality, especially the α-cellulose content. The dissolving pulp quality for each scenario is shown in Table 3-3. Another cooking process scenario would be necessary to increase the dissolving pulp quality to solve this problem.

Table 3-4 Dissolving pulp quality, furfural quantity, and environmental impact for each scenario

Scenario	Dissolving Pulp Quality				Furfural	LCA result per year			
	α-cellulose (%)	Viscosity (cP)	Brightness (%ISO)	Ash content (%)	Quantity (t/y)	AP	GWP100	EP	HTP
Existing	> 90.0% Good	> 6.2 Good	> 88.0 Good	< 0.15 Good	-	$5.75x10^{6}$	$9.16x10^{8}$	$1.50x10^{6}$	$2.66x10^{8}$
1	> 90.0% 83.0 Low	> 6.2 6.5 Good	> 88.0 90.4 Good	< 0.15 0.14 Good	27,794	$4.66x10^{6}$	$6.34x10^{8}$	$0.91x10^{6}$	$1.44x10^{8}$
2	83.0 Low	6.5 Good	90.4 Good	0.14 Good	55,588	$0.36x10^{6}$	$3.52x10^{8}$	$0.33x10^{6}$	$0.23x10^{8}$
3	96.4* Good	8.5 Good	90.7 Good	0.14 Good	3,705	$-2.01x10^{6}$	$-4.26x10^{8}$	$-0.73x10^{6}$	$-0.19x10^{8}$

Existing: Wood prehydrolysis/ kraft cooking followed by ECF bleaching

Scenario 1: Wood prehydrolysis/ kraft cooking followed by ECF bleaching (50%)

EFB acid prehydrolysis/ soda cooking followed by ECF bleaching (50%)

Scenario 2: EFB acid prehydrolysis/ soda cooking followed by ECF bleaching

Scenario 3: EFB water prehydrolysis/ soda-AQ cooking followed by ECF bleaching

Furfural production process: Dehydration + Distillation

AP: Acidification Potential in kg SO_2 eq

GWP100: Global Warming Potential in kg CO_2 eq

EP: Eutrophication Potential in kg PO_4^{3-} eq

HTP: Human Toxicity Potential in kg 1,4-DB eq

* [68]

3.3.3 Environmental impact contributor identification

Fig. 3-10 shows the environmental impact contributors in the production of 1 kg of dissolving pulp for each scenario. The major environmental impact contributor in the existing process is energy (electricity and steam), which contributes more than 60% of the total environmental impact value in the existing process scenario. Therefore, it is necessary to improve environmental performance by reducing electricity usage in the dissolving pulp production.

As mentioned before, the major environmental impact contributor is energy. The nitric acid prehydrolysis process can save the energy required for the soda cooking conducted at 104°C. However, nitric acid in the prehydrolysis process also contributes a significant environmental impact. Acidic conditions in the prehydrolysis process will provide sufficient amount of xylose for producing furfural as a co-product to produce more revenue. To improve environmental performance, replacing the nitric acid prehydrolysis with a water prehydrolysis process is an appropriate option.

3.3.4 Environmental impact assessment simulation of the improvement of the proposed process of integrated dissolving pulp and furfural production from EFB

Dissolving pulp quality can be improved by using a water prehydrolysis process (Scenario 3) instead of the nitric acid prehydrolysis. Table 3-4 shows that the α-cellulose content increased from 83.0% (Chapter 2) to 96.4% [68] upon using the water prehydrolysis (auto-hydrolysis by steaming) process. Moreover, this proposed process can reduce the environmental impact, as shown in Fig. 3-8. Scenario 3 is the most promising scenario of this study with negative environmental impact in the consequential approach, contributing -1.2178 kg CO_2

eq of GWP100, -0.0057 kg SO_2 eq of AP, -0.0021 kg PO_4^{3-} eq of EP, and -0.0538 kg 1,4-DB eq of HTP for producing 1 kg of dissolving pulp with 0.01 kg furfural co-production.

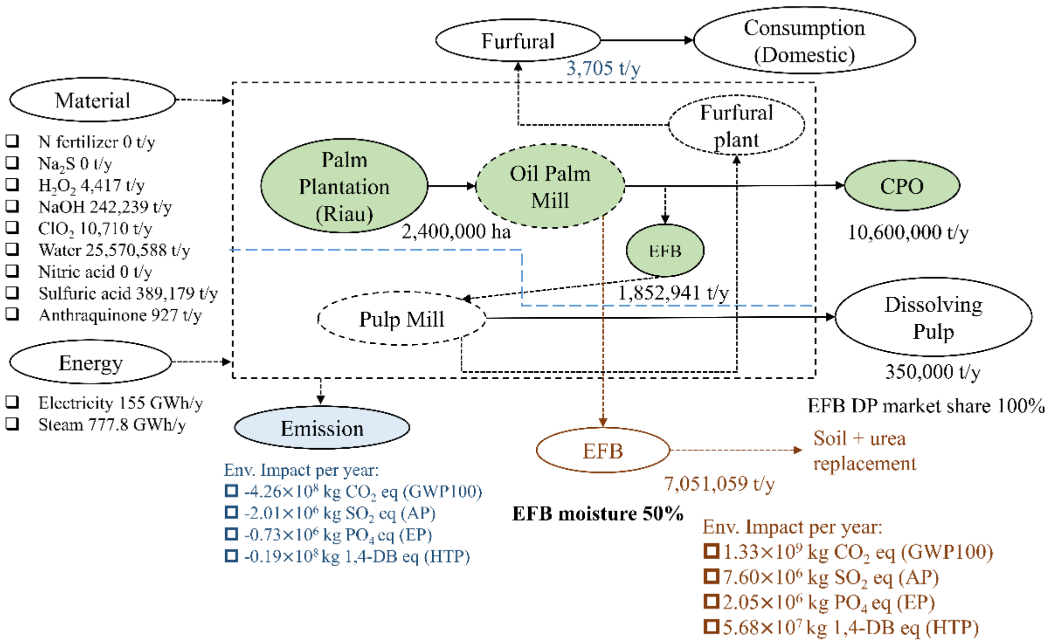
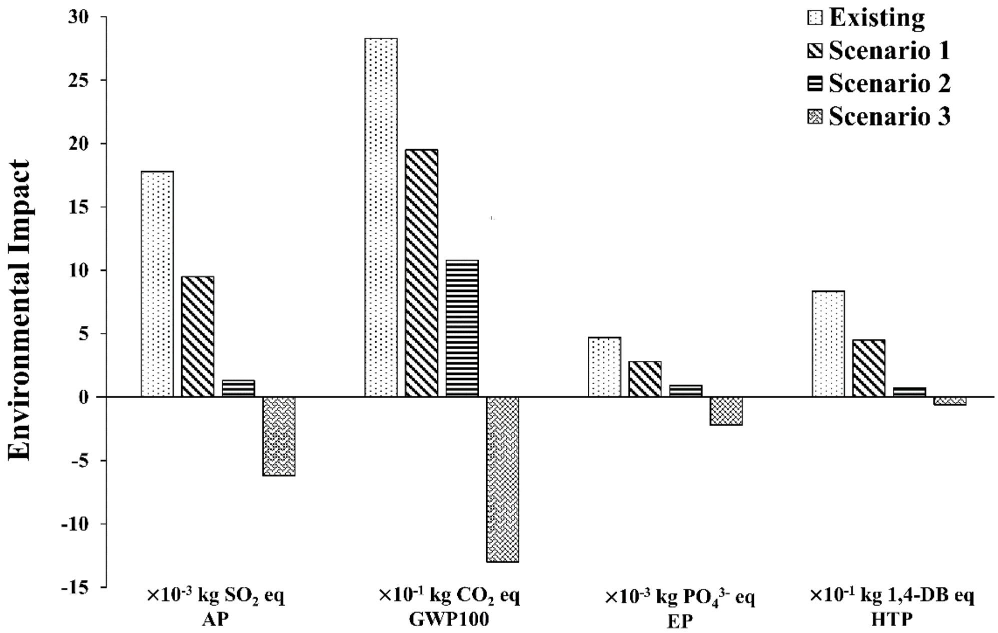


Fig. 3-8 LCI analysis and environmental impact assessment for proposed process with improvement by water prehydrolysis process (Scenario 3) to replace acid prehydrolysis process (Scenario 2)

However, Scenario 3 reduces the furfural co-product from 55,588 t/y to 3,705 t/y under the same conditions as Scenario 2. Acidic condition is necessary to obtain a high amount of hemicellulose required to produce furfural. Based on the furfural demand in Indonesia, this scenario is still sufficient to fulfill the demand.



Existing: Wood prehydrolysis/ kraft cooking followed by ECF bleaching

Scenario 1: Wood prehydrolysis/ kraft cooking followed by ECF bleaching (50%)

EFB acid prehydrolysis/ soda cooking followed by ECF bleaching (50%)

Scenario 2: EFB acid prehydrolysis/ soda cooking followed by ECF bleaching

Scenario 3: EFB water prehydrolysis/ soda-AQ cooking followed by ECF bleaching

AP: Acidification Potential

GWP100: Global Warming Potential

EP: Eutrophication Potential

HTP: Human Toxicity Potential

Fig. 3-9 Environmental impact assessment for 1 kg of dissolving pulp production (including furfural co-production in the proposed scenario 1, 2 and 3)

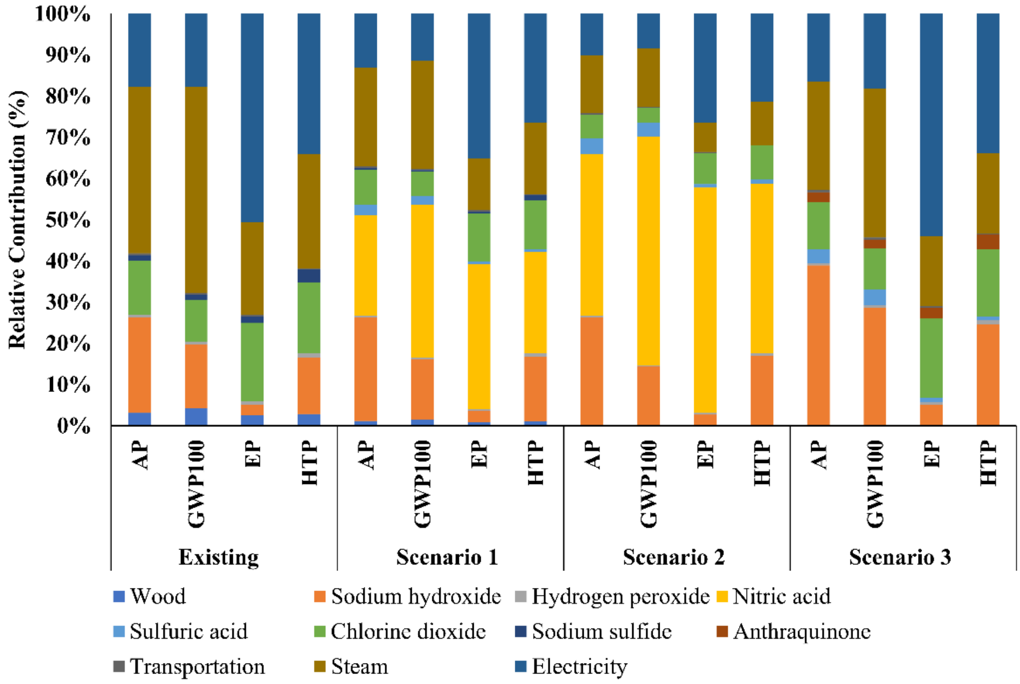


Fig. 3-10 Environmental impact contributor for 1 kg of dissolving pulp production in each scenario (including furfural co-production in the proposed scenario 1,2 and 3)

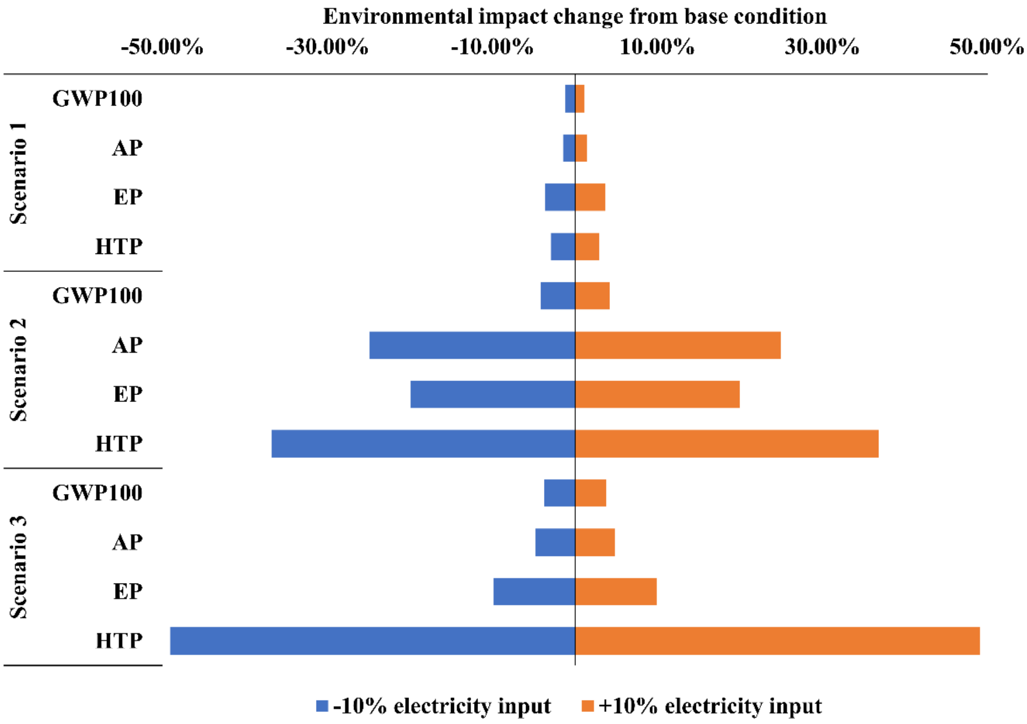
3.3.5 Effect of EFB utilization for integrated dissolving pulp and furfural production to additional agrochemical fertilizer usage

As shown in Figs. 3-6 to 3-8, EFB utilization for dissolving pulp and furfural production is 926,471 t/y for scenario 1 and 1,852,941 t/y for other scenarios. It was equivalent to 386.0 kg/ha/y and 772.1 kg/ha/y EFB that can be used for fertilizer, respectively. As a fertilizer, 1 ton of EFB is equivalent to 6.1 kg Urea [69]. Thus, an additional 0.001 t/ha/y Urea needs to be applied in Scenario 1 and 0.002 t/ha/y Urea for other scenarios. The environmental impact from this additional Urea is 8.88×10^{6} kg CO_2 eq of GWP100, 5.97×10^{4} kg SO_2 eq of AP, 1.94×10^{4} kg PO_4^{3-} eq of EP, and 5.53×10^{6} kg 1,4-DB eq of HTP per year. Based on this result, the increment of agrochemical fertilizer that was affected by the utilization of EFB for integrated dissolving pulp and furfural production was not significant. Moreover, oil palm plantation in Indonesia mostly still used chemical fertilizer as a major source of nutrients.

3.3.6 Sensitivity analysis on production process energy input for proposed scenarios

At the life cycle inventory level, the field survey and lab-scale experimental data used for material input can minimize uncertainty in the life cycle inventory level. According to the field survey in the conventional dissolving pulp production, the process conditions in the lab-scale experiment in this study were applicable in the industrial-scale. However, the uncertainty emerged from the energy input since it was collected from the literatures.

To investigate the influence of electricity and steam input parameters on environmental impact result, a sensitivity analysis was performed in the range of a 10% change in electricity and steam inputs. The additional environmental impact calculations were performed in the range of 10% above and below the baseline steam and electricity values shown in the life cycle inventory. The sensitivity analysis (Fig. 3-11) shows that within the same perspective, the HTP environmental impact category was significantly affected by a 10% difference in electricity and steam input. However, the climate change environmental impact category, such as GWP100, was not affected. The background data for electricity and steam production in this study were based on the EcoInvent LCI database.



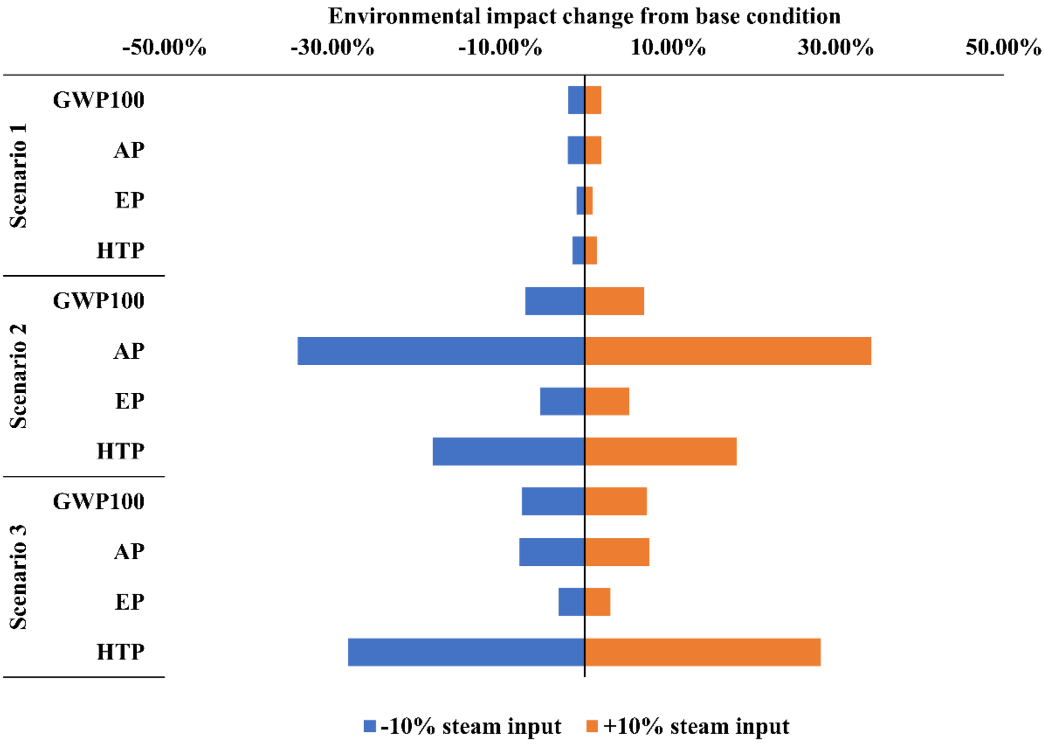


Fig. 3-11 Sensitivity analysis on production process energy input for proposed scenarios

3.3.7 Implication of LCA results for dissolving pulp industry decision support

The breakdown of the overall environmental impact in the existing and proposed scenarios through the consequential approach can satisfy industrial level decision-makers. Our analysis and study showed that the application of EFB as a raw material for valuable biorefinery products, such as dissolving pulp and furfural, were attractive based on the environmental point of view. For the palm oil industry, this proposed technology provides an alternative for EFB valorization. Additionally, the sustainability of the production of dissolving pulp in Indonesia will increase by the utilization of EFB as raw material while maintaining the quality of dissolving pulp. Moreover, other perspectives on the utilization of prehydrolysis liquor waste for furfural production are economically and environmentally attractive.

3.4 Conclusions

This research was conducted to propose EFB as the substitute of wood to produce dissolving pulp and furfural, which environmentally sustainable and economically profitable. The scenarios were proposed and compared with existing practice. The cLCA was conducted to evaluate Scenario 1 (50% of wood consumption was replaced by EFB), Scenario 2 (100% wood consumption was replaced EFB) and Scenario 3 (100% of wood consumption was replaced by EFB with environmental improvement in the prehydrolysis process). Scenario 3 was observed as the most promising scenario of this research. Moreover, the process in Scenario 3 maintains a dissolving pulp quality similar to that obtained using wood as raw material. Increasing the added value of EFB and decreasing the wood demand are key points of this development in addition to the environmental considerations. Furthermore, the environmental impact considering GWP, AP, EP and HTP were less compared to Scenario 1, 2 and existing practice. Therefore, in the commercial scale, EFB could be utilized for producing dissolving pulp and furfural production considering Scenario 3.

Chapter 4 Oil Palm Empty Fruit Bunch as A Promising Feedstock for Biorefinery Products in The Economic, Energy, and Environmental Consideration

4.1 Introduction

In the previous Chapter, the Scenario 3 was proved as the best scenario for dissolving pulp and furfural co-production based on environmental point of view. However, in the mass production, a comprehensive feasibility study based on cost and energy analysis was also needed. To overcome this problem, the techno-economic assessment (TEA), life cycle costing (LCC), and cumulative energy demand (CED) were done in this Chapter.

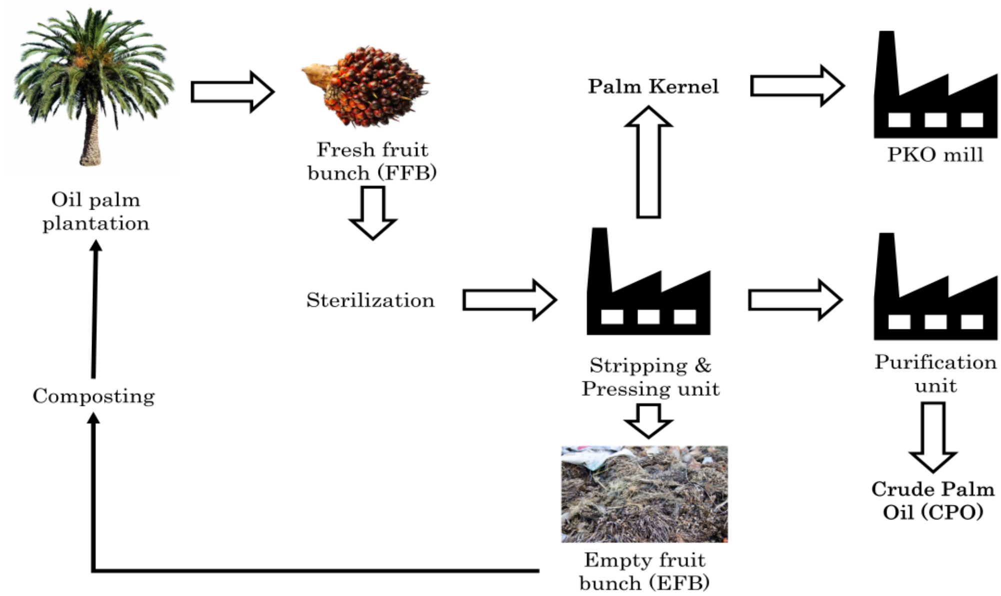


Fig. 4-1 CPO production process and EFB utilization scheme

Indonesian oil palm plantation areas are mainly located in Sumatra and Kalimantan islands. The distribution of oil palm plantations in Indonesia is previously shown (Fig. 3-3). 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 2016 [61]. 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. 4-1. Recently, EFB is used as an organic compost fertilizer in oil palm plantations [34,37].

Specifically, EFB is a rich carbon-source material that can be considered as a valuable material in the future. As shown in **Table 4-1,** the main chemical composition of EFB consists of cellulose, hemicellulose and lignin. Efforts focused on processing EFB into valuable products via mechanical and chemical treatments.

Table 4-1 Chemical composition of Empty Fruit Bunch (EFB)

Parameter	Composition based on dry weight EFB (%)		
	1	2[70]	3[29]
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

Mechanical treatment such as drying, shredding and pressing the EFB into briquettes, is a possibility in the EFB valorization pathway [71,72]. The obstacle to the mechanical treatment is the high moisture content of EFB (approximately 50%) which in turn is inefficient.

Additionally, chemical treatment (for 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, specialty papers, and viscose clothing [41]. Currently 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 processes [3].

Additionally, furfural is a diversified product from hemicellulose and is identified as one of the top thirty platform chemicals that can be made from biomass [16]. 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 EFB [73], rice husk [74], corn cobs [75] and sorghum straw [76].

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 [77,78], 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 [57,79,80]. 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 [9,48].

4.2 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. 4-2. The methodology consists of goal and scope definitions; environmental, economic and energy aspect assessments; and interpretation of each result.

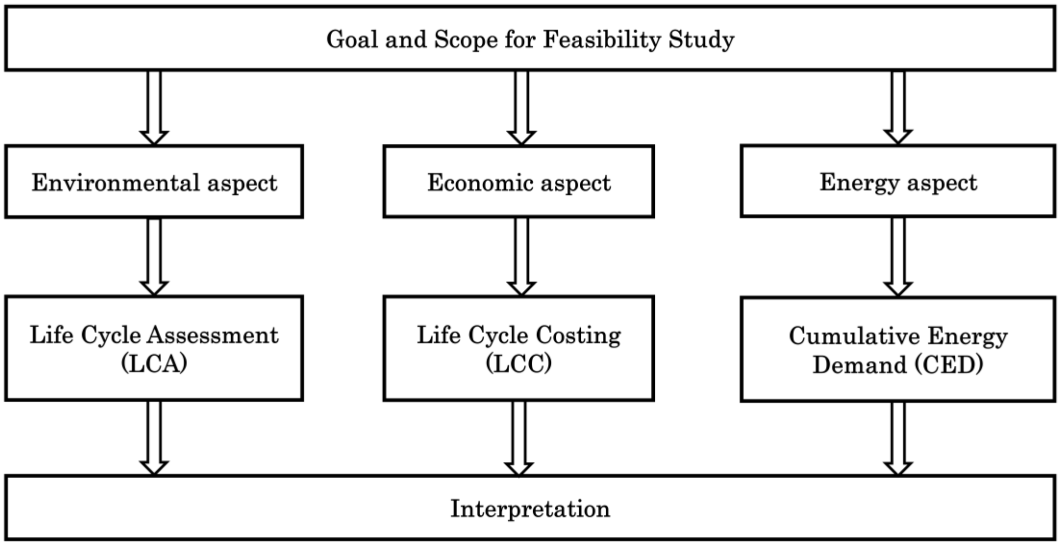


Fig. 4-2 Scheme of the methodology in this research

4.2.1 Goal and scope

The goal of the feasibility study is to evaluate the environmental impact, CED and LCC of dissolving pulp production by using prehydrolysis/soda-AQ cooking followed by ECF bleaching (scenario 3 in the previous Chapter). 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 and EFB extraction to dissolving pulp product and furfural co-product in the consequential approach. Fig. 3-4 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 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.

4.2.2 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 global warming potential (GWP) in kg CO_2 eq unit, eutrophication potential (EP) in kg PO_4^{3-} eq unit, acidification potential (AP) in kg SO_2 eq unit, and human toxicity potential (HTP) in kg 1,4-DB eq unit, were quantified. The GWP 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, respectively). Of these, GWP100 was used in the study. The EP corresponds to the prediction for over-accumulation of nutrients. The AP corresponds to the prediction of the over-accumulation of acidifying substance in the environment. The HTP is related to its effect on human health of toxic substances present in the environment [65]. The LCA calculation for environmental impact in each category is based on equation, as follows [65]:

$$Environmental\ Impact = \sum(E \times f_{substance}) \quad (4\text{-}1)$$

Specifically, E denotes emission in kg/kg of the functional unit; and $f_{substance}$ 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) [65]. The factor was expressed in kg CO_2 eq/kg of emission. The EP characterization factor was based on the stoichiometric procedure of CML impact assessment method and was expressed as kg PO_4^{3-} eq/kg of emission [63]. 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 SO_2 eq/kg of emission expression [81]. 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 emission [82].

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 as follows [83]:

$$\mathrm{LCC} = \sum(\mathrm{Q} \times \mathrm{P}) \qquad (4\text{-}2)$$

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)

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 as follows [84]:

$$\text{Annual earning} = \text{Annual revenues} - [\text{Operating costs} + (\text{a} \times \text{Investment costs})]$$

where

$$\text{a} = \frac{i}{1-(1+i)^{-n}} \quad (4\text{-}3)$$

where *i* is the interest rate; *n* is equipment lifetime

Equipment investment cost was calculated based on the six-tenth rule in equation as follows [85]:

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

The total cumulative energy input to the utilize EFB for dissolving pulp and furfural co-production was assessed via the cumulative energy demand (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 materials [86]. 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 as follows [87]:

$$CED=CED_P+CED_U+CED_D \quad (4\text{-}5)$$

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.

4.2.3 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 [29] and in the Chapter 2. The technical process conditions on EFB-based dissolving pulp process production via prehydrolysis/ soda-anthraquinone (AQ) cooking followed by elemental chlorine-free (ECF) bleaching are shown in Fig. 4-3. 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 D_0-E_p-D_1 (D_0: chlorine dioxide bleaching; E_p: extraction with peroxide; D_1: smaller dosage of chlorine dioxide bleaching than D_0). The bleaching conditions are listed in **Table 4-2**.

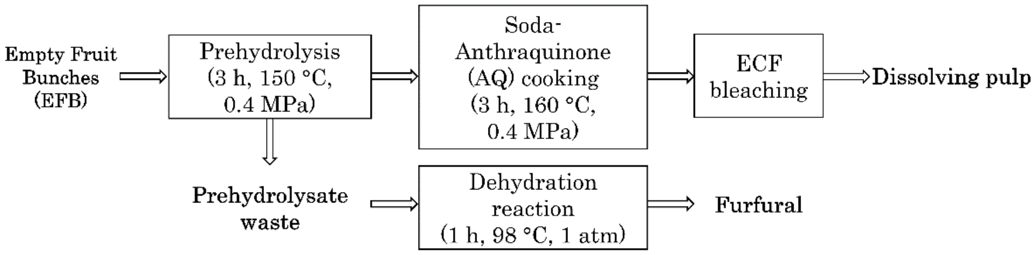


Fig. 4-3 Technical process diagram block of dissolving pulp and furfural co-production

Table 4-2 Bleaching conditions for proposed process

Bleaching sequence	Process conditions
D_0	ClO_2 dosage 2.9%; 1 h; 70 °C; PC* 10%
E_p	NaOH dosage 1%; H_2O_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; D_0: chlorine dioxide bleaching; E_p: extraction with peroxide; D_1: smaller dosage of chlorine dioxide bleaching than D_0

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 furfural[11)]. 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.

4.3 Results and discussion

Based on the system boundary described in Fig. 3-4 (Chapter 3), 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 obtained. 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 4-3 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% oven dried pulp yield based on oven dried raw material). 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.

Table 4-3 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	-29.25
H_2O_2	kg	0.013	41.00	0.53
NaOH for cooking	kg	0.683	37.00	25.27
NaOH for bleaching	kg	0.009	37.00	0.33
Chlorine dioxide	kg	0.031	60.00	1.86
Water	m3	0.073	120.00	8.76
Sulfuric acid	kg	1.112	21.30	23.69
Anthraquinone	kg	0.003	550.00	1.65
Energy				
Electricity	kWh	0.443	8.30	3.68
Steam	kWh	2.222	2.22	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	100.00
Furfural (co-product)	kg	0.011	1785.00	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 have not applied yet in Indonesia

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. 3-4 (Chapter 3).

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 CO_2 eq of GWP100, -0.006 kg SO_2 eq of AP, -0.002 kg PO_4^{3-} 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. 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 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 process [41]. Their study indicated that the total environmental impact to produce 1 kg of dissolving pulp in their process corresponded to 0.415 kg CO_2 eq of GWP100, 0.002 kg PO_4^{3-} eq of EP, 0.005 kg SO_2 eq of AP and 0.072 kg 1,4-DB eq of HTP [41]. 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 wood [88] 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 4-3 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 4-4.

Table 4-4 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
Investment costs		
Digester for dissolving pulp production[85]	JPY	2,764,667,090
Furfural plant[89]	JPY	209,341,039
Recovery boiler[86]	JPY	8,250,000,000
Causticization plant and lime kiln[85]	JPY	2,887,541,183
Heat exchanger system[84]	JPY	303,600,000
Piping system	JPY	122,100,000
Operating costs		
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

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 4-3 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. 4-6. 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.

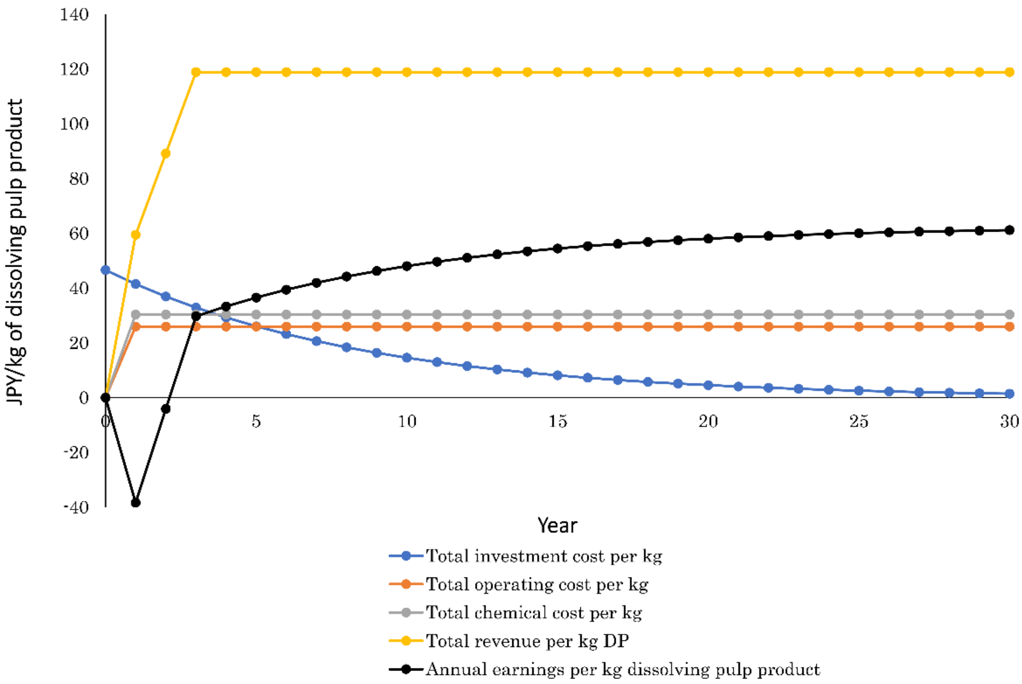


Fig. 4-4 Costs analysis for 1 kg of dissolving pulp production in the study

Based on annual earnings simulation for new plant of integrated dissolving pulp and furfural production in Fig. 4-4, positive annual earnings are obtained from third-year production. The annual earnings in third-year period were 7.43 billion JPY. This implies an earnings of 29.71 JPY per 1 kg 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 kg 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.

4.4 Conclusions

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 CO_2 eq of GWP100, -0.006 kg SO_2 eq of AP, -0.002 kg PO_4^{3-} 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.

Chapter 5 General Conclusions

The utilization of EFB as a raw material for integrated dissolving pulp and furfural production has been studied. In the laboratory experiment, nitric acid prehydrolysis soda cooking demonstrated that a furfural yield from the PHL was 6.2% of EFB material weight. The dissolving pulp demonstrated a brightness of 90.4% ISO and a viscosity of 6.5 cP, which were acceptable according to the Indonesian National Standard after ECF bleaching with P_{sa}-D_0-E_p-D_1 sequence using peroxymonosulfuric acid, chlorine dioxide, and hydrogen peroxide.

Based on the finding in Chapter 2, the Chapter 3 conducted to propose EFB as the substitute of wood to produce dissolving pulp and furfural based on environmental analysis. The scenarios were proposed and compared with existing practice. The cLCA was conducted to evaluate Scenario 1 (50% of wood consumption replaced by EFB), Scenario 2 (100% wood consumption replaced EFB) and Scenario 3 (100% of wood consumption replaced by EFB with environmental improvement in prehydrolysis process). Scenario 3 was observed as the most promising scenario of this research. Moreover, the process in Scenario 3 maintains a dissolving pulp quality similar to that obtained using wood as raw material. Increasing the added value of EFB and decreasing the wood demand are key points of this development in addition to the environmental considerations. Furthermore, the environmental impact considering GWP, AP, EP and HTP were less compared to Scenario 1, 2 and existing practice. Therefore, in the commercial scale, EFB could be utilized for producing dissolving pulp and furfural production considering Scenario 3.

In the Chapter 4, the focus is to evaluate the environmental impact, CED, and LCC of dissolving pulp production by using prehydrolysis/soda-AQ cooking followed by ECF bleaching (scenario 3 in the Chapter 3). The application of *waste-to-product* concept for EFB through 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 CO_2 eq of GWP100, -0.006 kg SO_2 eq of AP, -0.002 kg PO_4^{3-} 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 yield 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.

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