Biorefining of oil palm empty fruit bunches for bioethanol and xylitol production in Indonesia: A review

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Abstract
Indonesia has an intensive agro-industrial sector which evolves large volumes of residues each year. Currently these residues are under-utilized and have a deleterious impact on the environment, Oil Palm Empty Fruit Bunches (OPEFBs) in particular are highly abundant and offer good potential for conversion to bioenergy and bio-based products, in particular bioethanol and xylitol (widely used as an artificial sweetener and can substitute sugar in food and pharmaceutical industries). This paper provides a comprehensive review of the techno-economic opportunities and challenges for wider utilization of OPEFBs for the generation of bioethanol and xylitol in Indonesia. This review highlights the significant potential for valorization of OPEFB based on resource availability in the country (828 MWe/year or 45.86 Mt/year) and growing demand for both bioethanol (from 0.22 billion L in 2019 to 10.38 billion L in 2025) and xylitol (up to 2.20 kt in 2020). Various process configurations were explored to assess the potential for simultaneous co-production of bioethanol and xylitol. A mass balance and techno-economic assessment showed that the preferred scenario was Scenario 3 (co-production of bioethanol with xylitol and lignin) and that this has the potential to generate 46,145 kL bioethanol, 7.716 kt xylitol, and 25.704 kt lignin per year. This is significant given the limited production for both bioethanol and xylitol in the country currently. Further work is required to address challenges around technical, policy and supply chains. This work provides an original and novel strategy to support wider adoption of commercially viable bioethanol production in Indonesia.

Highlights
- Abundance of oil palm empty fruit bunches (OPEFB) creates prospect for biorefining
- Manufacture and supply of bioethanol and xylitol in Indonesia is feasible
- Multiple scenarios are proposed for mono- and co-production of bioethanol and xylitol
- Co-production of bioethanol and xylitol promotes sustainable bioeconomy
- Challenges remain on scalability, financial incentives and supply chain integration

Keywords: bio-based products; bioenergy; biomass valorization; biorefinery; circular economy
Word Count: 9,576 (include abstract, introduction to conclusions)

List of abbreviations including units and nomenclature:

AD	Anaerobic Digestion	OL	Organic Loading
ABE	Acetone-Ethanol-Butanol	OPEFB	Oil Palm Empty Fruit Bunches
BaU	Business as Usual	P(3HB)	Poly(3-hydroxybutyrate)
bio-SRF	Bio-Solid Refuse Fuels	PB	Sustainable Development or *Pembangunan Berkelanjutan*
CFC	*Contractor's Fee and Contingency*	PHA	Polyhydroxyalkanoate
CPO	Crude Palm Oil	PLTBg	Biogas Power Plant or *Pembangkit Listrik Tenaga Biogas*

DFC	Direct Fixed Cost	POM	Palm Oil Mill
DG NREEC	Directorate General of New, Renewable Energy, and Energy Conservation	POME	Palm Oil Mills Effluent
FC	Fixed Cost	PP	Payback Period
FFB	Fresh Fruit Bunches	PSSF	Pre-Hydrolysis Simultaneous Saccharification and Fermentation
FPU	Filterpaper Units	PST	Public Service Transport
GHG	Greenhouse Gas	RK	Low Carbon or *Rendah Karbon*
GIZ	The Deutsche Gesellschaft für Internationale Zusammenarbeit	ROI	Return of Investment
HMF	Hydroxymethylfurfural	RUEN	General Plan of National Energy or *Rencana Umum Energi Nasional*
IRR	Internal Rate of Return	SACG	Self-Adhesive Carbon Grains
KEN	National Energy Policy or *Kebijakan Energi Nasional*	Q-SSF	Quasi-Simultaneous Saccharification and Fermentation
Lac	Laccase Enzyme	SHF	Separated Hydrolysis and Fermentation
LHV	Low Heating Values	SHS	Super Heated Steam
LiP	Lignin Peroxidase Enzyme	SL	Solid Loading
MA	Maleic Acid	SS	Saturated Steam
MC	Moisture Content	SScF	Simultaneous Saccharification and Co-Fermentation
MDF	Medium Density Fiberboard	SSF	Simultaneous Saccharification and Fermentation
MEC	Major Equipment Cost	TGY	Total Yield Glucose
MEMR	Ministry of Energy and Mineral Resources, Republic of Indonesia	TPC	Total Plant Cost
MnP	Manganese Peroxidase Enzyme	*TPDC*	*Total Plant Direct Cost*
MSW	Municipal Solid Waste	*TPIC*	*Total Plant Indirect Cost*
NADH	Nicotinamide Adenine Dinucleotide (NAD) + Hydrogen (H)	VC	Variable Cost
NADPH	The reduced form of Nicotinamide Adenine Dinucleotide Phosphate	XKS	Xylulokinase Enzyme
Net B/C	Net Benefit Cost Ratio	XR	Xylose Reductase Enzyme
NPV	Net Present Value		

1. Introduction

Indonesia, like many developing nations, faces the challenge of providing access to clean, safe and affordable energy. Rapid population growth and expansion of industry have led to an increase in energy demand. However, inadequate infrastructure, centralized energy production and a lack of financial and policy instruments to support investment in technologies means that the country is not currently meeting its targets to increase the share of renewable energy up to 23% by 2025 and up to 31% by 2030 [1]. It has been estimated that, in 2019, fossil fuels (i.e. gasoline, coal and natural gas) accounted for 90.82% of all energy, while renewable energy (i.e. solar, hydro power, wind energy, and biomass) accounted for less than 10% [1,2]. In Indonesia, fossil fuels have significant environmental impacts (i.e. air pollution, greenhouse gas/GHG emissions) [3,4]; as well as negative impacts on human health [5,6]. Currently, renewable energy has good potential to address the challenges of energy supply and demands [7]; as well as fossil fuels depletion [8]. The ambition to shift to renewable energy has been translated into policy at a national level via the Indonesian Ministry of Energy and Mineral Resources

(MEMR) Regulation No. 20 Year 2014. This policy promotes the utilization of biomass for bioenergy and focuses on the creation of a national biofuel market. More recently, the MEMR Regulation No. 12 Year 2015 imposes the mandatory use of biofuels in Indonesia in transportation. Such regulation indeed has opened up potential market opportunities for biomass-based renewable energy [9]. Moreover, the Indonesian government has placed priority on the development of renewable energy from biomass resources, as stated in National Energy Policy/*Kebijakan Energi Nasional* (KEN) (Government Regulation No. 79 Year 2014) and General Plan of National Energy/*Rencana Umum Energi Nasional* (RUEN) in Presidential Regulation No. 22 Year 2017 [1]. The MEMR target for blending of 5% bioethanol in gasoline by 2020 and up to 20% by 2025, however a mandate for bioethanol blending in Indonesia has not yet been implemented. According to Setiawan et al. [10], the government is failing to promote blended bioethanol for transportation through targeted subsidy schemes. To fulfil domestic demand, Indonesia imports substantial quantities of gasoline from overseas. In 2015, 16.85 billion L (or 58% of its domestic gasoline demand) were imported, with demand increasing annually by 8% [11].

It is estimated that 11.9 billion tons (on a dry basis) of biomass is generated globally each year, with 61% (or 7.26 billion tons) derived from agricultural activities and 39% (or 4.64 billion tons) from forestry activities [12]. Lignocellulosic biomass contains three main components i.e. lignin, cellulose and hemicellulose. Lignocellulosic biomass is also called plant biomass, which can be grouped into several categories (a) forest residues, (b) agricultural residues, (c) grasses and (d) food industry wastes. Each biomass type has differing characteristics and composition [13,14]. Lignocellulosic biomass conversion generally releases 5-carbon and 6-carbon sugars, which can then be converted into biofuels (i.e. bioethanol, biohydrogen, etc.) and valuable biochemical compounds (i.e. xylitol, furfural, organic acids, etc.) [15]. The potential biomass supply in Indonesia is estimated to be 146.70 Mt/year including lignocellulosic biomass (such as rice straw, sugarcane bagasse, palm oil residues), municipal solid waste (MSW), industrial waste, etc. [9]. This biomass has an estimated potential supply of 31,461 MWe in 2016, as shown in Table 1. These wastes are cheap and renewable resources that can be captured and converted into bioenergy and other high value-added products, via an integrated biorefinery approach. Despite variation in the characteristics and composition, as seen in Table 1, these biomass types are suitable for bioethanol and xylitol production in isolation or co-produced.

Table 1. The potential bioenergy from biomass in Indonesia and its characteristics

No	Type of Biomass	Potential (MWe) [16]	Total (MWe) [16]	Biomass characteristics			References
				Cellulose (%)	Hemicellulose (%)	Lignin (%)	
1	Palm oil		12,655				
	- Fiber	1,231	-	19.0	15.2	30.5	[17]
	- Shell	758	-	14.7	16.4	53.6	[17]
	- OPEFBs	828	-	37.3 – 46.5	25.3 – 33.8	20.4 – 32.5	[18,19]
	- Palm oil mill effluent (POME)	431	-	na	na	na	-
	- Frond	8,430	-	33.46	13.95	30.92	[20]
	- Re-planting waste	977	-	na	na	na	-
2	Paddy		9,837				
	- Husk	1,461	-	35.31	22.60	26.11	[21]
	- Straw	8,376	-	40.54	20.80	12.87	[21]
3	Rubber		2,781				
	- Re-planting*	2,781	-	47.89	20.57	22.68	[21]
4	Municipal solid waste (MSW)	2,066	2,066	na	na	na	-
5	Corn		1,735				
	- Corncob	496	-	20.89-34.4	36.21-41.17	16.26-18.8	[22]
	- Stems and leaves	1,239	-	38.5	28.0	15	[23]
6	Sugar cane		1,295				
	- Bagasse	582	-	39.29	27.63	21.96	[21]
	- Sugar cane leaves and shoot	713	-	10.51-14.50	9.31-14.85	4.62-11.01	[24]
7	Cattle		535				
	- Manure	535	-	3.2	1.8	5.6	[25]
8	Wood		381				
	- Wood waste**	381	-	35.97	26.88	26.01	[21]
9	Coconut		176				
	- Coconut fiber	118	-	26.93	25.49	35.57	[21]
	- Coconut shell	58	-	30.58	26.70	33.30	[26]
Total			31,461				

Note: biomass characteristics as: *Rubber wood, ***Kamper* wood

In Indonesia, numerous studies have reported that lignocellulosic biomass, such as oil palm empty fruit bunches (OPEFBs), offer a promising route to sustainable biofuels (i.e. biodiesel, bioethanol, biohydrogen, and biogas) [27–31]; as shown in Table 2. Biodiesel is a liquid biofuel generated from a process of transesterification, yet production of biodiesel from biomass has not been widely adopted due to limited availability of commercially viable technologies and relatively low efficacy of the conversion process [32]. Biohydrogen is currently seen as a future, clean and renewable bioenergy sources, which can be generated through thermochemical (i.e. gasification, pyrolysis, supercritical waster extraction) and biological (i.e. fermentation, biophotolysis, combined dark-photo fermentation) routes [33]. Biohydrogen offers good potential but the infrastructure for supply and delivery is lacking. A study by Derman et al. [34], explored under-utilized OPEFB's across Malaysia. They confirmed that bioethanol from lignocellulosic biomass is more feasible than other conversion routes in term of its economic benefits and sustainability and can replace or blended with gasoline (due to its low cetane, high octane and heat vaporization). Also, use of bioethanol can reduce carbon emissions and minimize the consumption of fossil fuels [34–36]. A study by Vaskan et al. [37] and Medina et al. [38] focused on OPEFB utilization in Brazil and its potential for producing bioethanol, C5 syrup, xylitol, and lignin. These studies confirm that the valorization of lignin within the oil palm industries could offer multiple opportunities to improve economic and environmental sustainability. A study by Moncada et al. [39] in Columbia highlighted the potential for biorefining lignocellulosic biomass (i.e. OPEFBs) into bioethanol, biodiesel, and poly-3-hydroxybutyrate (P(3HB)). Beaudry et al. [40] and Huailuek et al. [41] emphasized that valorizing OPEFBs in Thailand via a biorefinery approach is promising in terms of economic viability and in terms of reducing environmental impacts of waste residues. Therefore, optimizing production of bioenergy from biomass through sustainable and commercially viable approaches is critical [42].

Table 2. Bioenergy prospects from OPEFBs conversion

Type of bioenergy	Conversion technology	References
Biogas	Pre-treatment, anaerobic digestion/AD (consists of 4 steps: hydrolysis, acidification, acetogenesis and methanogenesis)	[29–31,43]
Bioethanol	Pre-treatment, hydrolysis, fermentation (Separate Hydrolysis and Fermentation/SHF and Simultaneously Saccharification and Fermentation/SSF)	[34]
Biodiesel	Pre-treatment, transesterification	[44]
Bio-butanol	Enzymatic pre-treatment, simultaneous saccharification and acetone-ethanol-butanol (ABE) fermentation	[45]
Bio-oil	Fast pyrolysis, solvolysis (or liquefaction) both technologies can be used with and without catalyst	[46]
Biopower (electricity)	Pyrolysis, gasification, direct-firing, co-firing, and AD	[47]
Biohydrogen	Pre-treatment, hydrolysis, photo-fermentation	[45,48]
	Steam gasification	[49]
Biochar	Physical pre-treatment, pyrolysis	[50]
Bio-solid refuse fuels (bio-SRF)	Mechanical biological treatment	[51]
Hydrochar	Hydrothermal	[52]
Briquettes	Pre-treatment, briquetting	[53]
Bio-pellet	Physical pre-treatment, densification	[54]

Liquid fossil fuels account for approximately 35% of Indonesia's energy demand and the four-wheel vehicle market has grown substantially over the past two decades [55]. Setiawan et al. [10], estimated that four-wheels car sales will increase from approximately 1.1 billion vehicles (in 2018) to 1.7 billion vehicles (in 2030) due to the growth of population and a high income generation. This leads to an increase in gasoline consumption from 20.2 billion L (in 2018) to 49.5 billion L (in 2030). Bioethanol is a viable substitute for gasoline as traditional engines can easily be converted and the infrastructure for re-fueling is already well established in Indonesia. Geng [56] stated that commercial scale thermochemical conversion of OPEFBs, such as pyrolysis is challenging due to the complexity, high viscosity, and high water content of the resulted bio-oil. His study concluded that OPEFBs is not suitable for solid fuels production but has more potential for bioethanol as is contains highly fermentable organic material after pre-treatment. Gupta and Verma [35] reported that bioethanol yields from OPEFBs were 14.5%, much higher than that of from fruit peels (in the range of 3.98-8.34 %). They added OPEFBs has high bioethanol potential (i.e. about 16-fold higher than the actual world bioethanol production), making it a promising feedstock for scaled-up commercial exploitation. Johnson and Silvera [57] demonstrated the success of transitioning to bioethanol using existing infrastructure and policies of fuel blending and use of bioethanol in transportation sectors in Brazil, Malawi and Sweden. Globally, the production of bioethanol, continues to increase from 97.6 billion L (in 2015) to 109.9 billion L (in 2019) [58], making this conversion route an attractive opportunity for Indonesia and other countries processing OPEFB's. In 2019, the United Stated and Brazil led global production of bioethanol, with 54% and 30% of the world's bioethanol production, respectively. This is followed by the European Union which accounts for 5% and the rest of the world at 2%, with a gross value of 38.5 billion US$ of the total global production [59]. Rahmadi et al. [8] reported that, in Indonesia, conversion efficiency of biomass for bioethanol evolves higher yields (i.e. 6.47 kL/ha/year) than other fuel counterparts such as biodiesel (i.e. 4.50 kL/ha/year) and pure plant oil (i.e. 5.00 kL/ha/year). These findings indicate that production of bioethanol from biomass is a preferable conversion route offering relatively higher efficiency, sustainability, and economically feasibility compared with other conversion pathways.

In recent years there has been a greater focus on biofuels from waste resources rather than purpose grown crops. This gives further credence to the use of residues, such as OPEFBs [42]. Various lignocellulosic biomass can be converted into bioethanol, including used newspapers, rice husks, corn stover, wheat straw, cassava starch pulp, OPEFBs fiber [60]; and paper sludge, wood, waste hyacinth, etc. [61]. Each biomass will have unique physico-chemical characteristics which will determine which pre-treatment is most appropriate. It can be said that some biomass are more suited a particular conversion route based on their characteristics. Second-generation biomass (i.e. lignocellulosic biomass) is currently still seen as cost-effective and sustainable feedstock for bioethanol production, as previously stated by Prasad et al. [42].

Conversion efficiency of OPEFBs to bioethanol, is reported to be between 13.68 - 14.5% per raw OPEFBs [35,62]. Issues of converting OPEFBs are related to its high hemicellulose and lignin content, which can hinder the hydrolysis phase of conversion thus reducing the efficacy of bioethanol fermentation [34,63]. Improving the efficiency of the conversion process is critical to ensure that future bioethanol and xylitol production from OPEFBs is commercially and environmentally sustainable. Pre-treatment is often applied to enhance the production rate and total yield of monomer sugars at the hydrolysis stage. The conversion of (hemi) cellulose to monomeric sugars can be carried out chemically by addition of acids or enzymatically by the addition of cellulase (i.e. the enzyme responsible for the hydrolysis of cellulose). Fermentation of lignocellulosic material can result in increased concentrations of bioethanol. This can negatively impact on the microorganisms responsible for yeast and sugar fermentation which can, in turn impact on process stability. Therefore, pre-treatment is crucial to improve the characteristics of the biomass (i.e. removing lignin and reducing its crystallinity) [42,64]; aiming to achieve higher efficiency and efficacy of biomass conversion to bioenergy or other high value products [65].

OPEFBs can be utilized for the production of valuable biochemicals include xylitol, levulinic acid, succinic acid, guaiacol, vanillin, polyhydroxyalkanoate (PHA) and biofertilizer [66–68]; or other bio-based products. Table 3 provides the summary of various bio-based products that can be generated from OPEFBs and the conversion processes and technologies applied in each case. The market potential for xylitol has increased in recent years due to its applications in food and pharmaceutical products as a substitute for sugar and food additive [69]. In 2020, it was estimated that the potential global consumption of xylitol was approximately 242 kt (equal to gross revenue of 1 billion US$) [70]. There is limited information on the scale of xylitol production in Indonesia. According to Ahuja et al. [71], there are 14 leading xylitol's manufacturers from China, with total production of 196.3 kt/year. All these manufacturers use corn cobs as the main substrate. In the USA, DuPont (Danisco) is the leading manufacturer producing xylitol from birch trees or pulp and paper waste, with annual production of 2.0 kt.

Table 3. Prospect of bio-based products from OPEFBs

Type of bio-based products	Conversion technology	References
Medium density fiberboard (MDF) production	Physical pre-treatment, mechanical pulping, drying, blending with formaldehyde, forming, hot pressing, sanding	[72]
Pulp and paper production	Pulping, bleaching and blending	[72]
Compost/biofertilizer	Physical pre-treatment, co-composting	[68,72]
PHA	Pre-treatment (acid hydrolysis, enzymatic saccharification, microbial fermentation	[66]
Poly(3-hydroxybutyrate) P(3HB)	Physical pre-treatment, biosynthesis (microbial fermentation)	[73]
Xylitol	Pre-treatment, fermentation	[66,74]
Levulinic acid	Sequential depolymerization, esterification	[66,75]
Succinic acid	Pre-treatment, SSF	[66,76]
Guaiacol	Pre-treatment, depolymerization	[66]
Vanillin	Pre-treatment, oxidation, two-step fermentation	[66,77]
Ferulic acid	Physico-chemical pre-treatments (NaOH and autoclave)	[78]
Activated carbon	Physical pre-treatment, KOH chemical activation, microwave heating, physical steam activation	[79,80]
Supercapacitor electrodes (self-adhesive carbon grains/SACG)	Pre-treatment, KOH and CO_2 activation, heating	[81]
Liquid smoke (for biofungicides)	Drying, pyrolysis, condensation	[82]

Several studies have reported the opportunity for co-generation of bioethanol and xylitol from lignocellulosic biomass using a biorefinery approach [83–85]. This process integration could offer additional economic and environmental benefits.

This paper provides a comprehensive review of the challenges and opportunities of OPEFB conversion in Indonesia with a specific focus on mono- and co-production of bioethanol and xylitol production. The paper presents the technical challenges of pre-treatment, conversion and optimization of OPEFB's, which is abundant in Indonesia. Promising sustainable pathways for scaling-up and commercial production are presented and evaluated. These are based on peer reviewed studies and take into considerations factors such as biomass availability, valorization scenarios, mass balances, and economic analysis. These assessments aim to inform and support the wider promotion and adoption of bioethanol and xylitol industries in Indonesia.

2. Availability of OPEFBs in Indonesia

In 2019, Indonesia was the world's largest producer of oil palm with an estimated 45.86 Mt/year (accounting 75.69% of the global market). This is significantly higher than the 2nd and 3rd largest producers Malaysia and Thailand [86–88], as shown in Table 4. Oil palm is cultivated to produce oil palm fruit, where the fruit is extracted to produce vegetable oil and other derivatives, which are widely used by various industries and households around the world [65]. Demand for oil palm is continuously increasing in parallel to increasing global demand for food, energy, and other industrial processes**.** The oil palms are mostly used for Crude Palm Oil (CPO) production [87].

Table 4**.** Palm oil production based on potential area in the world (in Mt)

Year	Indonesia	Malaysia	Thailand	Global
2014	29.28	19.67	1.85	61.75
2015	31.07	19.66	1.83	58.92
2016	31.49	17.32	1.82	65.34
2017	34.94	19.20	2.60	70.58
2018	42.88	19.52	2.80	74.02
2019	45.86	19.58	2.90	72.27

Sources: FAO [86]; Hirschmann [87]; and Shahbandeh [88]

Palm oil contributes significantly to national development, yet, there exists significant conflicts between supporters of the palm oil industry and environmental conservationist (who raise concerns over land use exploitation, deforestation, peatland conservation and fire prevention). Furthermore, there is increasing government support for the utilization of OPEFBs for power generation for use within industry, as shown in Fig. 1, reported by Directorate General of New, Renewable Energy, and Energy Conservation (DG NREEC), MEMR and ExploRE Project, GIZ [89]. There are currently 700 palm oil mills (POMs) in Indonesia who have adopted on-site generation of bioenergy from OPEFBs, with an average production capacity of 30-45 tons fresh fruit bunches (FFB)/hour. These plants generate up to 3500 MW electricity by using the solids residual and 700 MW via biogas power plant (PLTBg) using the wastewater or palm oil mills effluent (POME) [16]. It has been identified that there is good potential for these mills to also generate bioethanol locally.

A study from Hayashi [90] suggests that the average POM in Indonesia produces 22.5% of OPEFBs; 14.3% of palm fibers; 6.7% of palm shells; 54.8% of POME; 5.4% of palm kernels; and 21% of CPO from 1 ton of FFB. Another study reported that for every ton of palm oil produced from FFB, approximately 1 ton of OPEFBs, 0.7 ton of palm fibers and 0.3 ton of palm shells are generated [46]. The largest amount of waste production from POM is OPEFBs and POME [91,92]. The OPEFBs contain lignin which is a recalcitrant component. The hydrogen bonds between the various layers of the cellulose chain, coupled with the cross-linking of lignin with cellulose and hemicellulose, forms a complex network of bonds that provide structural strength to the OPEFB [46]. Various studies have mentioned the lignocellulosic content in OPEFBs, for instance, Law et al. [18] found that OPEFBs has 44.2% of cellulose, 33.5% of hemicellulose, and 20.4% of lignin. Another study reported that, in Indonesia, OPEFBs contain cellulose of 37.3-46.5%, hemicelluloses of 25.3-33.8%, and lignin of 27.6-32.5% [19]. OPEFBs have higher lignin content compared to other lignocellulosic biomass in Indonesia, as shown in Table 1. The dominance of cellulose and hemicellulose of OPEFBs, as previously explained, and their potential relative abundance in relation to other biomass indicate that there are a huge potential for valorization of OPEFBs as feedstock for bioethanol and xylitol. Furthermore, the abundance of OPEFB means the cost implications and land use conflicts are minimal compared to other commercially available biomass feedstock

[34]. However, pre-treatment on OPEFBs are suggested in various studies aimed to enhance the conversion process.

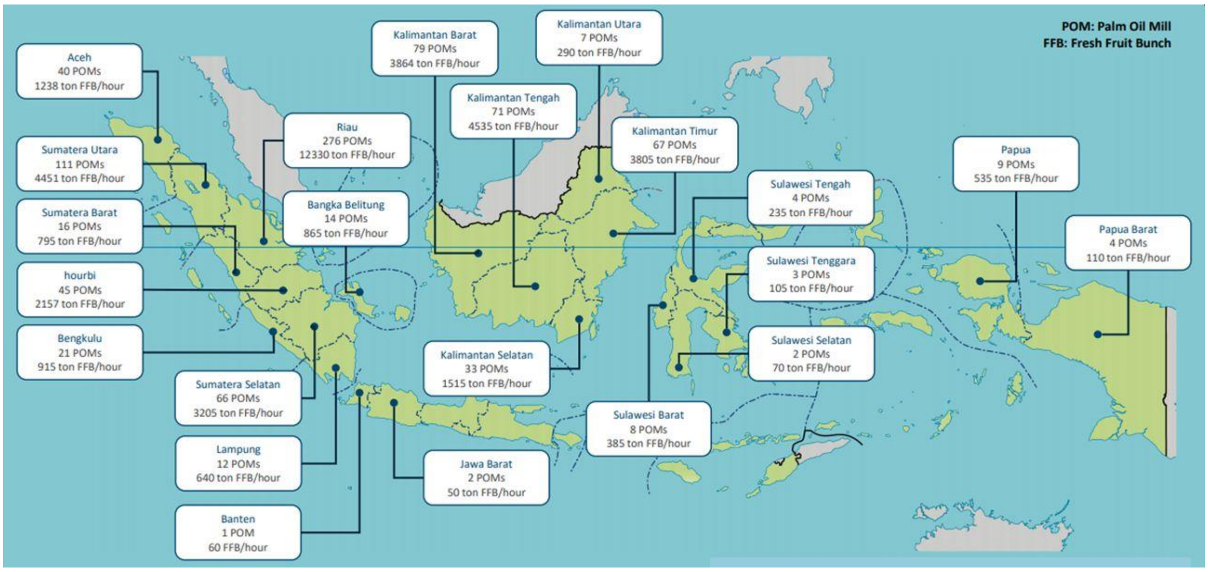

Fig. 1. Distribution of potential palm oil waste-based power plants as in 2021 (With permission from Directorate General of NREEC, MEMR and ExploRE Project, GIZ [89]). POMs: Palm Oil Mills, FFB: Fresh Fruit Bunches

3. Bioethanol and xylitol production from OPEFBs

3.1. Bioethanol

Bioethanol can be produced from any sugar-containing materials. Sugars, especially glucose, fructose, galactose, xylose and ribose, are used by microorganisms to produce energy from their own metabolism, as well as by-products, one of which is bioethanol [93]. Cellulose is the main component which is broken down (hydrolyzed) to produce sugars for bioethanol production. The efficacy and efficiency of this hydrolysis stage is dependent on the source of cellulolytic enzymes [94]. Cellulase enzymes can break the β-1,4 glycosidic bonds in cellulose and its derivatives. This enzyme is classified in the category of hydrolase enzymes, which include Endo-1,4-β endoglucanase (EC. 3.2.1.4), Exo-1,4-β-exoglucanase (EC. 3.2.1.91), and β-glucosidase or cellobioase (EC. 3.2.1.21) [42]. In general, bioethanol production from lignocellulosic biomass (i.e. OPEFBs) consists of pre-treatment, hydrolysis (enzymatic), fermentation, as shown in Fig. 2, then followed with product purification (i.e. distillation) [34,64].

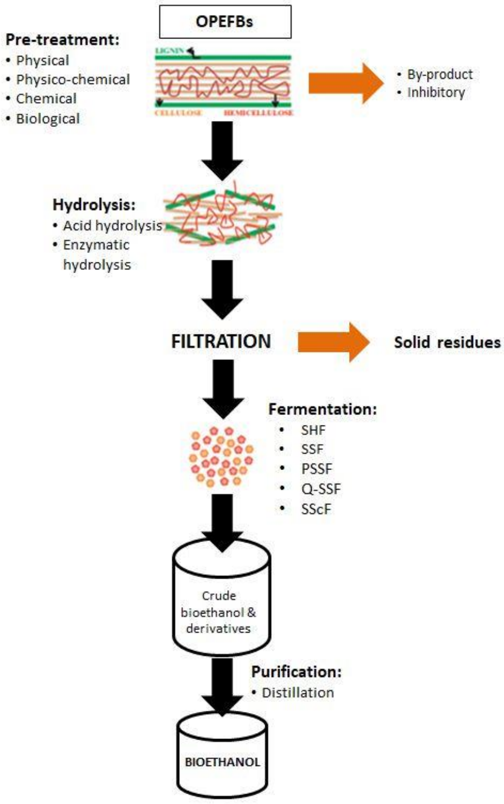

Fig. 2. Stages of the conversion process of OPEFB into bioethanol (Adapted from Derman et al. [34]; Hendriks and Zeeman [64]; and de Paula et al. [15]). SHF: Separated hydrolysis and fermentation, SSF: Simultaneous saccharification and fermentation, PSSF: Pre-hydrolysis simultaneous saccharification and fermentation, Q-SSF: Quasi-simultaneous saccharification and fermentation, SScF: Simultaneous saccharification and co-fermentation

In addition, 1 L of bioethanol can replace 0.66 L of gasoline, with low heating values (LHVs) of 32.19 MJ/L (gasoline) and 21.18 MJ/L (bioethanol) [95]. According to the MEMR [9], the main raw material for bioethanol production in Indonesia is currently molasses and cassava, however the government has also identified other potential biomass sources for bioethanol such as banana stalks, bagasse, straw and OPEFBs. Various studies on production of bioethanol from OPEFBs in Indonesia, with variation in operational condition, pre-treatment and conversion technologies are shown in Table 5. These studies indicated that pre-treatment, hydrolysis and fermentation methods are an important factor that determines the efficacy of bioethanol production from OPEFBs. For instance, Dahnum et al. [96] found that conversion of OPEFBs to bioethanol using SSF method was superior than that of with SHF method, resulted in 21% higher ethanol yields.

Table 5**.** Bioethanol production from OPEFBs in Indonesia

Operational condition and microorganism	Fermentation process	Fermentation time (h)	Scale	Glucose yields (g/L)	Bioethanol yields (g/L)	Refs.
• Pre-treatment: dried, cut, and soaked in 10% NaOH solution (temperature of 140-145 °C, pressure of 4-7 kg/cm^2, and duration of 30 min) • Treated OPEFBs was neutralized with water and H_2SO_4 97% to pH 7-9 • Enzymatic hydrolysis: cellulase (Novozyme) 34 FPU and enzyme β-glucosidase (Novozyme) 4.8 L – Saccharification enzymatic: temperature of 50-52 °C, pH 4.8-5.5, 12 hours • Local *Saccharomyces cerevisiae* Mk (4L)	SSF	48	Pilot (235 L, 32 °C)	89.02	51.40	[19]
• Pre-treatment: dried, cut to ~ 3mm, and soaked in 10% NaOH solution (temperature of 150 °C, pressure of 4-7 kg/cm^2, and duration of 30 min.) • Treated OPEFBs was washed and dried to 10% moisture content (MC) • Substrate loading rate (15, 20, 25 g/mL), • Enzymatic hydrolysis: Cellic® Ctec2 (18 FPU/g) and 20% Cellic® Htec2 (based on Cellic® Ctec2 volume) • Yeast *Saccharomyces cerevisiae* (1 %w/v)	SSF	72	Laboratory (250 mL, 32 °C, 150 rpm)	0-31.65	45.50-83.40	[97]
• Pre-treatment: 10% NaOH, 150 °C, 30 min, solid:liquid ratio (1:5) • Substrate loading rate: 15 g/mL • Enzymatic hydrolysis: Cellic® CTec2 (10, 20, 30, 40 FPU/g) and Cellic® HTec2 (20% of Cellic® CTec2 added) • SSF with addition of dried yeast *Saccharomyces cerevisiae* (1 g/mL)	SHF and SSF	72	Laboratory (SHF-50 °C, 150 rpm) (SSF-32 °C, 150 rpm)	10.67 (SHF)	18.75 (76 %-SHF) 23.93 (97%-SSF)	[96]
• Pre-treatment: 8% NaOH, 100 °C, 10-90 min • Enzymatic hydrolysis: cellulase and β-glucosidase, 45 °C, 24 h • *Mucor indicus*	SSF	96	Laboratory (37 °C)	-	16.88 (68.4%)	[98]
• Pre-treatment: Microwave-assisted glycerol-sulfuric acid • Glycerol: sulphuric acid ratio was 1:20 (w/v), stirring for 20 min, radiation 5-15 min. (550 W) • Enzymatic hydrolysis: Meicelase enzyme (20 FPU/g) • Yeast *Saccharomyces cerevisiae*	SSF	72	Laboratory (38 ± 2 °C	-	1.26	[99]
• Pre-treatment: NaOH solution, 150 °C, 4 bars, 30 min • Enzyme: CTec2 and HTec2 with ratio 5:1 • Yeast *Saccharomyces cerevisiae* (1%w/v)	SSF	72	Laboratory (250 mL, 15% w/v, 32 °C, 150 rpm)	-	62.00	[100]
• Pre-treatment: Microwave-assisted maleic acid (MA) pre-treatment (160-200 °C, 2.5 radiation time, 1% (v/v) MA • Pre-hydrolysis: 50 °C, 120 rpm, 4 h • Enzymatic hydrolysis : cellulase (40 FPU/ g dry OPEFBs) • Local *Saccharomyces cerevisiae* InaCC Y93	SSF and pre-hydrolysis SSF (PSSF)	72	Laboratory (38 °C, 120 rpm)	-	18.90 (76.6%-SSF) 9.94 (80.78%-PSSF)	[101]

Table 5. Bioethanol production from OPEFBs in Indonesia (Cont.)

Operational condition and microorganism	Fermentation process	Fermentation time (h)	Scale	Glucose yields (g/L)	Bioethanol yields (g/L)	Refs.
• Pre-treatment: dried, cut 2-3 mm, and soaked in 10% NaOH solution, 150 °C, 4 bars, 30 min • Enzymatic hydrolysis : cellulase (Cellic® Ctec2 and Cellic® Htec2) • Yeast *S. cerevisiae*	SSF	72	Laboratory (32 °C, 150 rpm)	-	39.00	[102]
• Pre-treatment: cut 1-3 mm, soaked in 10% NaOH (autoclave at 150 °C, 4 atm, 30 min) • Enzyme Ctec2 (Novozymes) • pH medium of SSF adjusted to 4, 5.0 and 5.5. • Encapsulated *R. oryzae*	SSF	96	Laboratory (37 °C, 150 rpm)	Reduced from 20 g/L to 1 g/L	33.92 (pH 4.5) 38.92 (pH 5.0) 37.66 (pH 5.5)	[103]
• Pre-treatment: dried, cut to 1 cm, organoslov (ethanol at 1:10 of solid-liquid ratio) • Enzymatic hydrolysis: 60 FPU/g, temperatures (35 °C, 70 °C, and 90 °C), time (2-24 h) • Yeast *Saccharomyces cerevisiae* (1%w/v)	SSF	84	Laboratory (35 °C, 150 rpm)	1.53	0.63	[104]
• Pre-treatment: soaked in NH_4OH solution at ratio of 1:5 (w/v), 24 h • Enzymatic hydrolysis: cellulase enzyme Cellic Htec (48 h, 50 °C, 130 rpm) • *Zymomonas mobilis*	SSF	12	Laboratory (30 °C, 100 rpm)	3.2	0.20-0.25	[105]
• Pre-treatment: grinding to 50-80 mesh, soaked in 1% NaOCl for 5 h, dilute NaOH or H_2SO_4 8%, autoclave and microwave • Enzymatic hydrolysis: xylanase and cellulase at pH 6 • Yeast *Saccharomyces cerevisiae*	SSF	72	Pilot (50 L fermenter)	-	76.4	[106]
• Pre-treatment: KOH solution • Acid hydrolysis: 1% H_2SO_4 , 90 °C, 1 h • Yeast *Saccharomyces cerevisiae* (concentration of 4 g/L, 6 g/L, and 8 g/L)	SSF	96	Laboratory (30 °C, 250 rpm)	112.44	41.411	[107]

3.2. Xylitol

Xylitol is an artificial sweetener with similar sweetness level to sucrose, having a lower calorie content of 2.4 kcal/g and a glycemic index of less than 19 [70,108]. The xylitol is produced from xylose which is a monosaccharide with five carbon atoms, one aldehyde functional group at position 1 (aldopentose) or ketone at position 2 (ketopentose). Xylose ($C_5H_{10}O_5$) itself is released from the hemicellulose structure [109,110].

There are various chemical and biological pathways for the conversion of xylose to xylitol, as shown in Fig. 3. Chemical processes involves catalytic hydrogenation of xylose at high temperature (80-140 ºC) and high pressure (~50 atm), while biological process (fermentation) uses microorganisms (yeast strains) that can convert xylose to D-xylulose through oxide-reductive pathway or enzymatic approach [22,70,74,108,111,112]. According to Rafiqul and Mimi Sakinah [113] and Rao et al. [70], there are further xylose reduction pathways which involve the presence of enzyme xylose reductase (XR) with the use of cofactors (i.e. NADH and/or NADPH), followed by conversion in the presence of enzyme xylulokinase (XKS). However, during the conversion of xylose, various rate-limiting factors or inhibitors (i.e. acetic acid, hydroxymethylfurfural (HMF), furfural, total phenolic acid, formic acid, levulinic acid) may present which can negatively affect the xylitol production [70,110,114]. Therefore, detoxification of hydrolysate is essential, including chemical processes (i.e. use of activated charcoal, ion-exchange resin), nanofiltration (i.e. membrane separation, reverse osmosis), vacuum membrane distillation, electrochemical, and biological processes (i.e. the use of microorganism such as *Coniochaeta ligniaria* or enzymes such as laccases and peroxidases) [70,113,115]. A comparison of xylitol production methods, their advantages and disadvantages is provided in Table 6. The table indicates that for the application of xylitol production from OPEFBs, use of biological routes with xylose-fermenting yeast and enzyme offers better xylitol yield and the conversion efficacy is greater. With this approach, OPEFBs residues from xylitol extraction can then also be used as feedstock for bioethanol production offering greater potential commercial and environmental benefits. This approach has previously been reported in a number of recent studies [38,83,116].

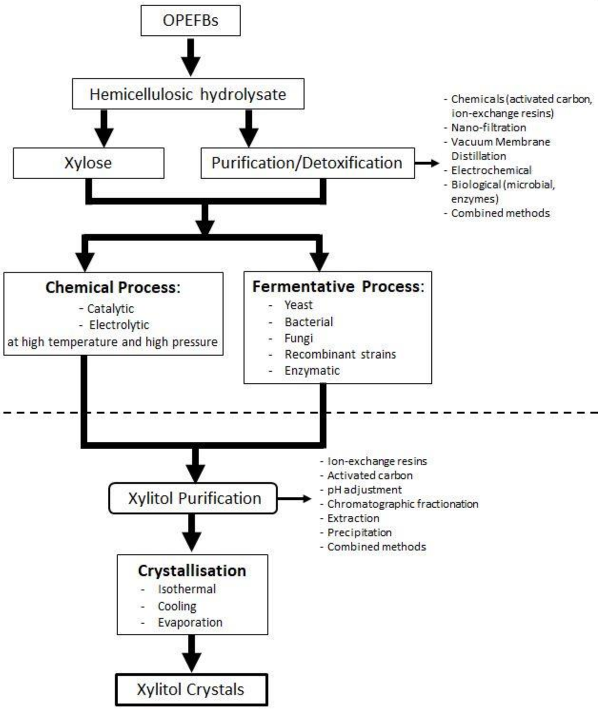

Fig. 3. Flow chart of xylitol production – chemical, biological and thermochemical processes (Adapted from Rao et al. [70]; Irmak et al. [117]; Rafiqul and Mimi Sakinah [113]; Martínez et al. [118])

Table 6. Comparison of xylitol production methods in various literatures

Methods	Procedures	Xylitol yield	Advantages	Disadvantages	Ref
Chemical	Chemical hydrogenation using catalyst at high temperature and high pressure	50-60 %	• Non hydrogenated sugar is separated easily • High purified xylose production	• Energy intensive • Extensive separation and purification steps • High cost of technology and operation • Labour extensive • Low efficiency process • Non-ecofriendly and sustainable process	[113–115,119]
Biological	Microbial process (or fermentation): - Xylose-fermenting yeast For example *Enterobacter liquefaciens*, *Corynebacterium sp*., *Mycobacterium smegmatis*, *Gluconobacter oxydans*, *Candida guilliermondii*, *Debaromycess hasenii*, and etc. - Fungi For example *Penicillium chrysogenum, Penicillium roqueforti* CCT 1273, *Verticillium crustosum* CCT 4034, *Penicillium brevicompactum* CCT 4457, *P. chrysogenum* CCT 1273, *Penicillium purpurogenum* CCT 2008, *Penicillium citrinum* CCT 3281, *Penicillium janthinellum* CCT 3162, *Penicillium griseoroseum* CCT 6421, *Penicillium expansum* VIC, *Penicillium italicum* DMBI, *Aspergillus niger* DMB2, and etc. - Bacteria For example *Gluconobacter cerinus* IFO 3262, *Gluconobacter oxydans*, *Streptomyces coelicolor*, *Acetobacter pasteurianus*, *Agrobacterium paraffineus*, *Erwinia amylovora*, and etc. - Recombinant strains	65-85 % 0.14-0.52 g/L 0.1-5.5 g/L 86-100%	• Cost effective • No needs for xylose purification • Savings energy • Wide substrate availability • High efficiency process (i.e. high productivity) • Eco-friendly and sustainable process	• Need pre-treatment for lignocellulosic biomass • Sensitive to inhibitions • Time consuming • Cell recycling problem • High water consumption • Problems of culture media	[112–114,119,120]
	Enzymatic approach: - Xylose reductase (XR) from yeast	96-100%	• Non-cell recycling limitation • Savings energy and water • High efficiency process (i.e. high yield and productivity) • Eco-friendly and sustainable process	High cost of enzyme preparation	[112–114,119]

With regards to the utilization of OPEFBs for xylitol production, the reported studies are limited. These are summarized in Table 7. In general, the findings indicate that the efficacy of the selected pre-treatment step, together with the condition and mode of fermentation operation can significantly affect the overall efficacy of xylitol production. The review also highlighted that biological conversion of OPEFBs using enzymatic approach offers highest yield, followed by xylose-fermenting yeast then chemical approach. Xylose-fermenting yeast is widely used in Indonesia for the biological approach of transforming OPEFBs into xylitol. However, when implementing a biological conversion route, there is a need to improve the biosynthesis efficacy of xylitol and selection of highly efficient xylitol-fermenting microorganism through metabolic engineering and microorganism modification [120].

Table 7. Summary of previous studies on xylitol production from OPFEBs

Microorganism	Detoxification methods	Hydrolysis	Fermentation mode and conditions	Xylitol yield	Refs
Debaryomyces hansenii ITBCCR85	No	Enzymatic (crude xylanase enzyme extract), 45 ºC, pH 4.7	Batch, SSF, addition of synthetic xylose, 30 ºC, semi-aerobic condition, 450 rpm, pH 5	0.24 g/g	[74]
Debaromycess hasenii	No	Enzymatic (10% xylanase), incubated at 50 ºC, 96 h	Batch, 30 ºC, 200 rpm, pH 5, aerobic condition, ratio hydrolysate: inoculum solution: medium (2:2:3)	0.03 - 0.079 g/L	[121]
Candida guilliermondii	No	Dilute-acid, 2-6% H_2SO_4	Batch, 30 ºC, 200 rpm, 96 h, pH 5.5, aerobic condition	10.3 g/L	[122]
Debaromycess hansenii	na	na	Batch, 30 ºC, semi-aerobic condition	0.11 g/L	[123]
Debaryomyces hansenii	No	Enzymatic (10 mL Cellic HTec 2 with activity of 750 U/mL), 60 ºC, 150 rpm, pH 5.0	Batch, SSF, 30 ºC, 150 rpm, 96 h	0.104-0.201 g/L	[124]
Debaryomyces hansenii ITBCCR85	No.	Enzymatic (Cellic HTec 2 and Cellic CTec 2), 50 ºC, 150 rpm, pH 5, 72 h	Batch, SSF, 30 ºC, 450 rpm, pH 5, 7 days	0.41 g/g	[125]
Debaromyces hansenii ITB CCR85	No	Enzymatic (Cellic HTec 2), solid loading (5% w/v), pH 55.2, 30-42 ºC, 150 rpm, 48 h	Batch, SSF, addition of inorganic salts solution, 30-37 ºC, 150 rpm, 72 h	0.08 g/g	[126]

4. Pre-treatment of OPEFBs to bioethanol and xylitol production

The selection of a pre-treatment method can greatly affect economics as it improves the conversion efficiency, as well as adding significant overall cost to the conversion process [127]. Lignocellulosic biomass pre-treatment can be classified into physical, chemical, physicochemical and biological processes [14,42]. Effective pre-treatment will separate each lignocellulose component without needing additional removal step. The selection of pre-treatment is also influenced by the crystallinity of lignocellulose, degree of polymerization, accessible surface area to improve degradation and acetyl groups on the substrate [14]. These considerations are important to yield lignocellulosic materials that are more pliable and accessible to enzyme attack to enhance cellulose-hemicellulose hydrolysis [128]. Incomplete or insufficient removal of lignin can reduce the hydrolysis rate and decrease the digestibility, therefore it is essential to remove all lignin prior to hydrolysis to ensure higher C5 and C6 sugar production [128,129].

A study by Hendriks and Zeeman [64] highlights that thermo-chemical pre-treatment (e.g. utilization of steam plus acid, base or Organosolv with organic solvent) can also be applied to lignocellulosic biomass. In recent decades, several pre-treatment methods have been identified, evaluated and demonstrated at lab-scale, pilot scale or industrial scale [127]. Due to its relatively low energy and chemical consumption, biological pretreatment still offers the best potential. Selection of effective lignin-degrading microorganism to improve biodegradation and thus process performance remains a challenge. This remains critical to promoting wider commercial adoption and deployment of this approach. Physio-chemical and chemical pre-treatment remain feasible options for enhancing lignocellulosic biomass to bioethanol due to their high productivity, commercial scalability, and its high lignin removal efficacy. However, these approaches require higher initial investment costs and significant environmental control measures to ensure safety and minimize environmental impacts. These factors should be carefully considered when scaling up.

Pre-treatment methods are used to produce monomers from the OPEFBs that then have the potential to be used as a fermentation feedstock for bioethanol. A review of these methods has been conducted and a summary can be seen in Table 8. It can be seen that two approaches are commonly applied as a first step. These include mechanical size reduction (usually <1 cm or into a powder) and acid pre-treatment. The use of acids tends to degrade hemicellulose while alkaline tend to degrade lignin. The more concentrated the chemicals, both acid and alkaline, the higher the total sugar produced hence the conversion to monomers during hydrolysis is higher. Acid pre-treatment is more widely used and is considered more efficient for the conversion of OPEFBs, as well as results in a higher ethanol yield than other methods [129]. Acid pre-treatment can increase cost (due to additional safety precautions or corrosion resistant vessels) and is not considered to be environmentally sustainable (due to additional requirement of safe disposal of waste chemicals or wastewater) [34]. According to Azelee et al. [128], alkaline pre-treatment has a high efficiency in the lignocellulose delignification allowing further enzymatic hydrolysis and resulting in fewer by-products. NaOH can also be considered a less toxic and corrosive chemical solution, as well as widely used as safe solvent solution in hydrolysis or extraction process [130,131]. Derman et al. (2018) added that pre-treatment using biological agents, i.e. fungi, are proven to be more environmentally friendly, but only a relatively small amount of bioethanol is produced. However, using the fungi approach, OPEFBs recovery of lignin is very high. White-rot fungi for example is highly effective due to the presence of lignin peroxidase (LiP), laccase (Lac) and manganese peroxidase (MnP) enzymes, which degrade lignin into CO_2 and H_2O macromolecules [132].

Table 8. Summary of previous studies on pre-treatment for enhancing bioethanol production from OPFEBs

No	References	Treatment type			Results		
		Pre-treatment	Hydrolysis	Fermentation	Pre-treatment	Hydrolysis	Fermentation
1	Piarpuzan et al. [133]	Physical (10 mesh/ 2 mm), alkaline (NaOH 2%), and *steam* (117 kPa /121 ºC for 6 seconds)	Enzymatic	using *S. cerevisiae*	Total sugar = 10.3 g/L (Increased by 63.5%)	Total sugar = 18.12 g/L (Increased by 27.7%)	Bioethanol was 4 g/L
2	Millati et al. [134]	Dilute acid H_2SO_4 (0.2% and 0.8%) at 170ºC-230 ºC for 5 and 15 minutes	na	using *Mucor indicus* and *S. cerevisiae*	• Xylose increased to 135.94 g/kg OPEFB (0.8%, 190 ºC, 5 min) • Glucose increased to 62.7 g/kg OPEFB (0.8%, 190 ºC, 5 min)		Bioethanol yield was 0.45 – 0.46 g/g sugar consumed
3	Han et al. [62]	Physical (1-3 mm) and alkaline (NaOH 2.89 ml/L)	Enzymatic	SSF using *S. cerevisiae*	Total sugar increased by 93.28%	Total sugar increased	Bioethanol was 46.02 g/L (Bioethanol yield increased by 86.62%)
4	Kim and Kim [135]	Dilute acid (H_2SO_4 4%) and concentrated alkaline (NaOH 10M)	Enzymatic	SSF using *S. cerevisiae*	• Cellulose increased by 114%) • Hemicellulose = 1.8 g • Lignin degraded by 70%	The production of glucose is higher and xylose is very low	Bioethanol yield was 37.8 g/L
5	Tan et al. [136]	Physical (0.3–0.45 mm), oxygen-catalyzed, and chemical (sodium bisulfite/ $NaHSO_3$ 8% and sulphuric acid H_2SO_4 1%)	Enzymatic	Q-SSF using *S. cerevisiae*	• Glucose yield = 0.318 g/g EFB • Glucan = 60.78% • Xylan = 2.18% • Lignin = 20.44%	Cellulose is converted by 83%	Bioethanol was 52 g/L (Bioethanol yield increased by 95%)
6	Chiesa and Gnansounou [65]	Physical and dilute acid (H_2SO_4 1.5%)	Enzymatic	na	Total glucose increased by 40%	Total glucose increased by 85%	na
7	Ishola et al. [132]	Physical (10 mm), white-rot fungi *Pleurotus floriandus* and phosphoric acid (H_3PO_4 85.7%)	Enzymatic	SSF using *S. cerevisiae*	Cellulose increased by 37.5% Hemicellulose decreased by 60.3% Lignin increased by 8.3%	na	Bioethanol yield increased by 62.8%
8	Medina et al. [137]	Steam explosion (195 ºC for 6 seconds)	na	na	Cellulose increased by 24% Hemicellulose decreased by 68%	Total sugar = 4.2 g/L	na
9	Bouza et al. [138]	Physical (1 mm) and acid (H_2SO_4)	Enzymatic	na	Glucan = 8.24% Xylan = 81% Lignin = 4.94%	Glucan was up to 74.8% and Xylan increased by 81.4%	na

Table 8. Summary of previous studies on pre-treatment for enhancing bioethanol production from OPFEBs (Cont.)

No	References	Treatment type			Results		
		Pre-treatment	Hydrolysis	Fermentation	Pre-treatment	Hydrolysis	Fermentation
10	Nurfahmi et al. [104]	Physical (1 mm) and Organosolv (C_2H_5OH 55%)	Acid (H_2SO_4 0.5%)	Yeast culture	Total sugar = 98.89 mg/L (derived from cellulose and hemicellulose)	Total sugar = 152.51 mg/L	Bioethanol yield was 62.29 g/L
11	Palamae et al. [139]	Physical (3 mm), paracetic acid (CH_3CO_3H) and alkaline (alkaline peroxide)	Enzymatic	na	• Cellulose = 81.9% • Hemicellulose = 11.2% • Lignin decreased by 98%	• Glucose production = 629.8 g/kg EFB • Xylose production = 61.2 g/kg EFB	na
12	Tye et al. [140]	Water, acid (H_2SO_4), and alkaline (NaOH)	na	na	• Water pre-treatment at 170 ºC and 30 min): total yield glucose (TGY) =40%; cellulose removed by 100% • Acid pre-treatment at 120 ºC, 45 min, and 2% v/v): TGY= 34%; cellulose removed by 100% • Alkaline pre-treatment at 110 ºC, 45 min, and 3% v/v): TGY = 33%, lignin removed by 84.1%	• Water pre-treatment can hydrolyze >99.9% sugar • Acid pre-treatment can hydrolyze 89.3% sugar • Alkaline pre-treatment can hydrolyze >99.9% sugar	na
13	Kamoldeen et al. [141]	Physical (drying 72 hours) and alkaline solution (3% NaOH with solid-liquid charge of 1: 8, temperature 110 ºC for 45 minutes	na	SScF	• Holocellulose increased by 91% • Lignin decreased by 71%	na	Bioethanol yield increased by 84.9%
14	Azman et al. [142]	Microorganism *Stenotrophomonas sp.* S2	na	na	• Cellulose removed up to 100% • Hemicellulose decreased by 80.4% • Lignin degraded by 50%	na	na
15	Mardawati et al. [143]	Physical (grinding to 20, 50, and 80 mesh, drying overnight at 105 ºC), Organoslov (ethanol at solid-liquid ratio of 1:10), 160 ºC (for 40, 65 and 90 min)	na	na	• Lignin degraded by 27.68 %	na	na

The amount of lignin, cellulose and hemicellulose in OPEFBs greatly influences the conversion of organic matter to xylose and then to xylitol. As with bioethanol production, various physical, chemical, thermal and biological pre-treatments are available. Rao et al. [70] stated that physical pre-treatment aims to disrupt the integrity of the lignocellulosic substrate so that it is able to increase the accessibility of acids or enzymes to the substrate. Their study also illustrated that pre-treatment using acid was found to be most widely used to remove lignin and reduce the crystallinity of lignocellulosic biomass to facilitate saccharification and conversion to xylitol. Mardawati et al. [121] reported that extracting xylose from powdered OPEFBs increased efficiency of conversion, thus improving final xylitol concentrations. Meilany et al. [144] found that combining physical and hydrothermal pre-treatment on OPEFBs was best to generate higher xylose, which can then further be converted to xylitol. Whilst studies on effect of pre-treatment for xylitol production from OPEFBs are limited, a summary of those identified are shown in Table 9.

Table 9. Summary of previous studies on pre-treatment for enhancing xylitol production from OPFEBs

Pre-treatment	Key findings	Refs
Physical (i.e. cut, dried at 60 ºC for 24 h, grind to 60 mesh)	Xylitol concentration: 0.033-0.079 g/L	[121]
Physical (i.e. dried at open air, cut 10-12 cm, washed with water, dried at 60 ºC for 24 h, grind to 60 and 80 mesh), followed by hydrothermal pre-treatment (autoclave)	Xylose yield: 0.06 g/g	[144]
Physical (i.e. disinfected, oven-dried at 60 ºC for 24 h, milled to 0.05 and 4 cm)	Xylose concentration: 32.60 g/L	[122]
Sequence acid/alkaline using 8% H_2SO_4 and 40 % NaOH	Fermentable sugars: 84.1 g/L	[145]
Ultrasound (20 kHz, 2000 W, 45 min., 25 ºC), followed by acid 2% H_2SO_4	Xylose yield: ~53%, Glucose yield: ~5%	[146]
Physical, steam/ auto-hydrolysis (0.28 MPa/140 ºC)	Total sugars: 209 g/kg OPEFBs	[147]
Physical (i.e. cut, dried and grind to 80 mesh), followed by autohydrolysis (121 ºC, 15 min.)	Xylose utilization: 85-100%	[124]
• Physical (i.e. washed, dried, shredded to 1-2 cm) followed by steam explosion at 160 and 200 ºC, 0.6 and 1 MPa for 5 min. • Physical, with chemical pre-treatment (i.e. H_2SO_4 or NaOH solution), followed by steam explosion (same condition as above)	Xylose yield: 0.003-0.021 g/g (SHS) 0.014-0.020 g/g (SS) 0.018-0.088 g/g (acid –SS/SHS) 0.012-0.014 g/g (alkali-SS/SHS)	[148]
Physical (i.e. washed, sun dried, grind to 60 mesh), followed by autohydrolysis (with water, acetic acid or ammonia) using autoclave at 25% (w/v) solid to liquid ratio, 120.2-127.9 ºC, 1-1.5 barg, and 15-90 min.	Xylose yield: 0.02-0.085 g/g	[125]

Notes: SHS= superheated steam, SS= saturated steam

This review has provided an overview of the current state of art in both bioethanol and xylitol production. This evidence base is used to explore various process configurations and the opportunities and challenges of co-production via a biorefinery approach.

5. Future opportunities for scaling-up and commercialization in Indonesia

5.1. Market potential for bioethanol and xylitol

It is important to understand the potential scale and nature of bioethanol and xylitol markets in Indonesia in order to identify the most opportune routes for deployment. Currently, there is limited data on the number and location of bioethanol plants in Indonesia. Those that have been identified are small scale and dispersed geographically. In 2019, the bioethanol production was reported to be 0.40 million L/year [2]. Based on the Indonesia Energy Outlook report, it is projected that bioethanol demand and supply are continuing to increase as shown in Fig. 4 [1]. In this report three scenarios are explored, including Business as Usual (BaU), Sustainable Development/*Pembangunan Berkelanjutan* (PB), and Low Carbon/*Rendah Karbon* (RK) scenarios. These scenarios make the basic assumption that the gross domestic product growth will be 5.6%/year and population growth rate will be 0.7%. The estimation of bioethanol demand as an energy source has increased to 50% and 85% in PB and RK scenarios, while only 5% in BaU scenario (Fig. 4a), which was partially due to increasing economic and population growth. This report also estimates that the increase in new and renewable energy supply in Indonesia is influenced by the use of 100% biodiesel and 85% bioethanol to provide energy used in transportation, industry, and commercial sector (Fig. 4b). Therefore, there is open investment potency for further scaling-up and commercialization of bioethanol production from OPEFBs.

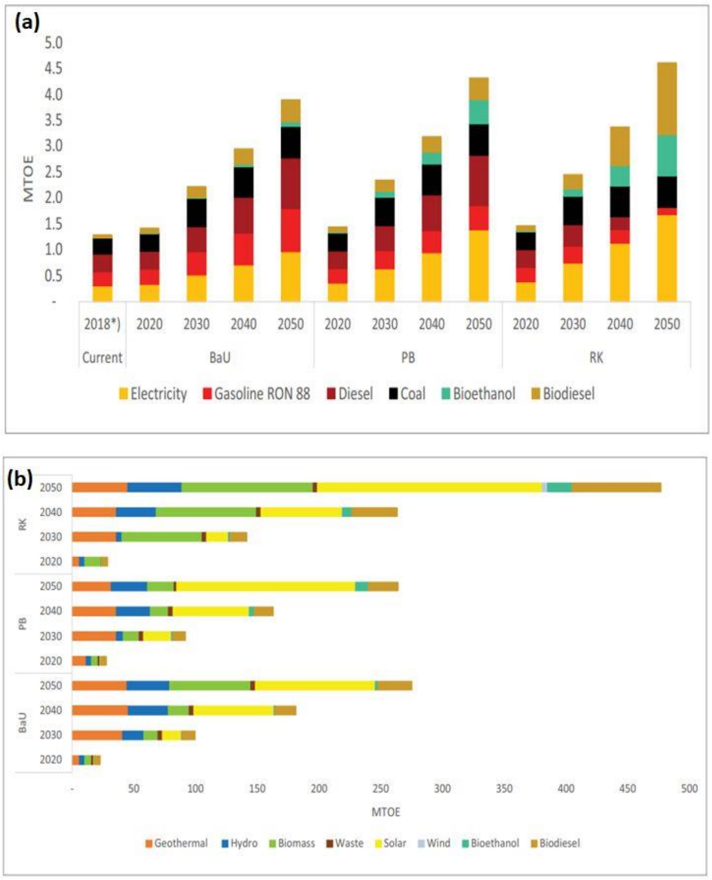

Fig. 4. Trend and projection of (a) bioethanol demand and (b) supply in Indonesia (With permission from Secretariat General of the National Energy Council, MEMR [1]). BaU: Business as Usual, PB: Sustainable Development/*Pembangunan Berkelanjutan*, RK: Low Carbon/*Rendah Karbon*

According to the US Department of Energy, xylitol is one of the highest value bio-based chemicals which can be produced from lignocellulosic biomass [149]. Xylitol has wide applications especially food (as sweetener and as an additional ingredient to improve colour, taste and shelf life of confectioneries and chewing gums), odontological (due to incidence of dental caries and remineralization properties), and pharmaceutical (as it has prebiotic effects) [115]. Ahuja et al. [71] reported that the use of xylitol in chewing gums and confectionery products accounted for approximately 70% of the global market share. Several clinical trials and comprehensive analysis have been reviewed in Mäkinen [150], that small daily amounts of xylitol significantly reduces the dental caries incidence and notably chewable xylitol products (i.e. chewing gums, lozenges, troches, and hard caramels) have turned out to be useful. Ur-Rehman et al. [115] explained that xylitol has less calories and a lower glycemic index which is good for diabetic patient management. It is considered to be an ideal alternative sweetener or sugar substitution for the control of blood glucose, lipid level, and body's weight.

There has been a significant increase in demand for xylitol due to an increase in consumer's awareness of food products which are sugar free and low calorie [70]. Annual sales of xylitol globally is estimated to be in the region of 823.6 million US$ and estimated to increase to 1.4 billion US$ by 2025 [119]. Production of xylitol in Asia markets accounted for 50% of the global xylitol production, while Europe, United States and Australia account for the remaining global xylitol production capacity [151], and this is estimated to continuously increase [70]. Rao et al. [70] stated that xylitol consumption was predominantly driven by the chewing gum industry which consumed an estimated 163 kt (or 67% of the global xylitol consumption) in 2020. Mostly, xylitol demand has been fulfilled from the chemical conversion of hydrolysates from lignocellulosic biomass [119]. The Indonesian Bureau of Statistic reported that, in 2008, the xylitol demands in Indonesia were fulfilled by importing from other countries which amounted to 576 tons (or 41.9 million US$) [152], and the demand continues to increase to up 2.0 kt in 2020. The scale and nature of the global xylitol market together with predicted future demand provides further evidence to support an increase in local production in Indonesia where manufacture is currently limited.

5.2. Scenario Evaluation– Technical and Economic Assessment.

5.2.1. Potential Process Configurations

Several scenarios were proposed and evaluated in order to highlight the technical and commercial opportunities for conversion of OPEFBs in Indonesia. These scenarios were based on the production of either xylitol or bioethanol in isolation (mono-production) or combined production via process integration (co-production). The proposed process pathways are presented (Fig. 5) together with an estimated mass balance and economic assessment. For Scenario 1, xylitol or bioethanol is produced in a single process stream, however, organic solid residues are generated as by-products which contain organic materials (such as lignin, cellulose, glucan, or xylan), have potential for production of high value chemicals.

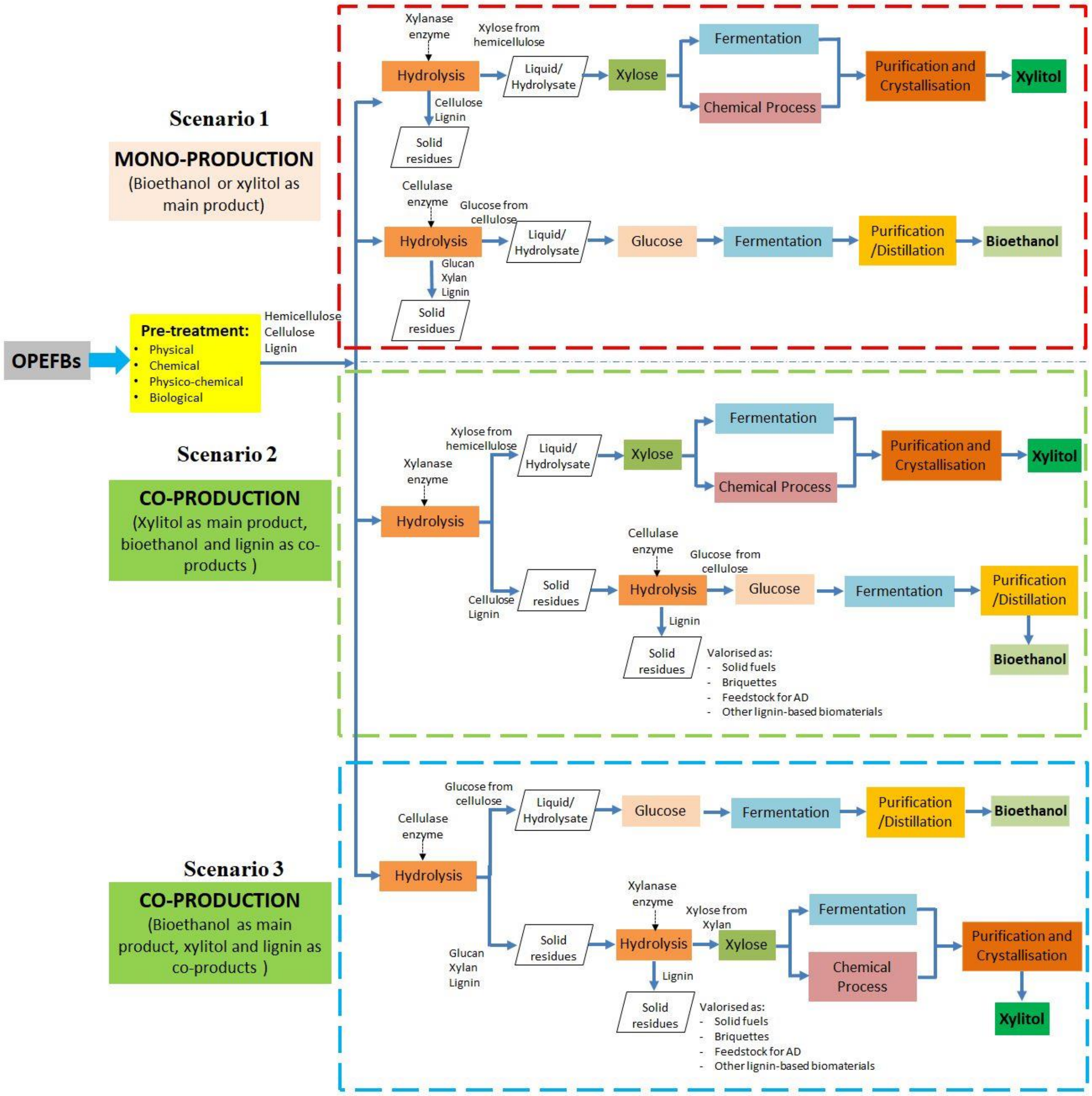

Fig. 5. Scenarios of OPEFBs valorization into bioethanol and xylitol production

Scenarios 2 and 3 propose co-production with a primary process stream focusing on either bioethanol or xylitol production with further valorization of residues to produce a secondary high value product. Biorefining of OPEFBs has been demonstrated for a variety of products. A study by Raman and Gnansounou [153] demonstrated that OPEFBs could be effectively utilized for the production of furfural, bioethanol, and lignin, with integration of dilute sulfuric acid pre-treatment to enhance the process. Vaskan et al. [37] also indicated that transforming OPEFBs into bioethanol and C5 syrup (for cattle feed), power, and heat was economically feasible and environmentally sustainable. While Hafyan et al. [67] found that conversion of OPEFBs into value-added chemicals (i.e. xylitol, levulinic acid, succinic acid, guaiacol, and vanillin) using a biorefinery approach offered greater economic and environmental benefits, as well as improved safety (through improved management of wastes).

Other studies have demonstrated that co-production of xylitol and ethanol from other lignocellulosic biomass using a biorefinery approach is feasible. Cheng et al. [154] showed a potential sequential configuration producing xylitol and bioethanol from corncob, with consideration that one weight unit of xylitol equivalent with eight weight units of cellulosic-rich solid residues. Another example is demonstrated by Xavier et al. [155], who found that xylitol and bioethanol can be produced simultaneously from sisal (*Agave sisalana*) fiber using *Candida tropicalis* CCT 1516 yeast combined with dilute acid pre-treatment at low temperatures. Shankar et al. [156] also reported that co-production of xylitol and ethanol from banana and water hyacinth leaves is feasible using *Candida tropicalis* and *Saccharomyces cerevisiae*. Song et al. [157] reported that production of bioethanol and xylose with co-production of xylitol and xylulose under simultaneous process conditions resulted in increased profits due to improved cost competitiveness.

Despite the clear opportunities and technical feasibility for co-production of xylitiol and bioethanol, there are limited studies available in the literature demonstrating this. Harahap and Kresnowati [125] reported that ethanol can also be produced during xylitol production by *Debaryomyces hansenii* from OPEFBs. The species *D. hansenii* has the ability to catabolize xylose to xylitol and glucose to ethanol. Their study explained that OPEFBs pre-treated with autohydrolysis formed liquid fractions and residual solid fractions. The liquid fractions contain high concentrations of dissolved xylose that are sufficient for xylitol fermentation, while the solid fractions are rich in glucose for ethanol fermentation. Based on the findings of this review, 2 (two) co-production scenarios are proposed which evolve multiple high value products, including xylitol, bioethanol, and lignin. In scenario 2, xylitol is proposed as the main product due to its high market value, following bioethanol fermentation. Bioethanol is produced from the residual OPEFBs derived from hydrolysis of xylose, as it still contains high amount of cellulose. This scenario may be a good fit for existing xylitol manufacturers globally where retrofit of additional process streams could transform the solid waste stream into bioethanol. Alternatively there is opportunity here for establishment of new commercial xylitol production. Scenario 3 is aimed at producing bioethanol as the primary product, with co-products of xylitol and lignin. This scenario is targeting existing bioethanol manufacturers who could expand production by adding xylitol production using the solid residues stream resulting from bioethanol fermentation. Bioethanol production in Indonesia is limited with the majority of producers utilizing molasses as a feedstock. Several POMs produce biodiesel from CPO or use residual fiber for generating electricity via off-grid biomass power plants. No information could be found on POMs producing bioethanol from wastes [16].

Within all scenarios, lignin-rich solid residues are generated after fermentation of bioethanol or xylitol. The solid residues offer potential for conversion into additional high value-added products (i.e. briquettes, boiler feed, biogas, chemicals, or other lignin derivate products), which could enhance the economic and environmental benefits of this approach [153]. Hafyan et al. [67] showed that lignin-rich residues from OPEFBs can be converted into highly valuable chemicals such as guaiacol and vanillin. While Ahmad et al. [158]

reported that lignin-rich residues from OPEFBs can be used for producing fuels, chemicals, carbon fibers, and polymer (i.e. lignin graft copolymer).

5.2.2. Mass balance

According to Chang et al. [46], for every tons of palm oil produced there is 1 ton of OPEFBs generated as waste. Based on the reported yields of palm oil in Indonesia (as shown in Table 4), this equates to approximately 45.86 Mt of OPEFBs. The potential yields of xylitol and bioethanol were calculated according to Mardawati et al. [74,105,111] and Goh et al [159], respectively. The data are used to develop a mass balance for Scenario 1, 2 and 3 based on 1000 kg of raw OPEFBs, as shown in Fig. 6, 7 and 8. A detailed mass balance for the proposed scenarios is provided in Table 10 and Table S1-4 in the supplementary data. The summary of estimated potential production can be seen in Table 11. In this calculation, the concentration of cellulose, hemicellulose, lignin and other components in OPEFBs are based on the values described in Law et al, [18]. While the hemicellulose is assumed to contain xylose (19.62%) and arabinose (1.5%) [160]; xylan (24.01%) [161]; and glucose (35.8%) [162]. Fig. 6a illustrates bioethanol production from OPEFBs. The first step is pre-treatment which composed of physical treatment (milling) to reduce the particle size. This is followed with dilute alkaline (NaOH 10%) pre-treatment added at loading rate of 20% (or ratio of 1:5; OPEFBs:NaOH), based on a study described by Dahnum et al. [96]. This alkaline pre-treatment is aimed to disrupt the OPEFBs cell wall, such that more cellulose is exposed for enzymatic breakdown. During the hydrolysis (or saccharification), cellulase enzyme is added to enhance the breakdown of cellulose into glucose. The filtration process is designed to separate lignin and other impurities from the hydrolysate, with a calculated total of 510.30 kg of residual solids generated. While the sterilization is proposed to prevent contamination during fermentation. Fermentation, would be carried out in separate system (also known as SSF), with addition of yeast *Saccharomyces cerevisiae* (at loading rate of 1%). The bioethanol production is estimated by using a formula described in Goh et al. [159], which is based on the efficiency of conversion recovery from glucose and xylose from cellulose and hemicellulose of OPEFBs. The paper stated that the conversion efficiency ratio of hemicellulose to xylose and cellulose to glucose are 0.90 and 0.76, respectively, while, the fermentation efficiencies for xylose to bioethanol and glucose to bioethanol are 0.50 and 0.75. Using this formula, it is calculated that approximately 352.49 kg (or 35.25%) of crude bioethanol could be generated from conversion of glucose and xylose to bioethanol. In the distillation process, it is assumed to use extractive distillation process with two columns, having the ability to enhance bioethanol purity in the range of 99.5% to 99.8% [37,163–165]. While other compounds such as xylose, glucose and biomass would remained as solid residues at the bottom of the column and 92.5% of water is released in vapor state [37]. Using this configuration process, the mass balance based on previous work illustrated that from 1000 kg of OPEFBs, 352.49 kg (or 35.25%) of bioethanol could potentially be produced with purity of 99.8%. Therefore, based on the mass balance in Fig. 6a, the total potential bioethanol production from OPEFB in Indonesia (based on 2019 availability) is approximately 17.12 Mt/year.

Data from the MEMR [1,16] shows that bioethanol demand is projected to increase to 10.38 billion L by 2025, yet the bioethanol production is currently only 0.40 billion L/year (as data in 2019). Therefore, this data indicates that there is a significant potential for further valorization of OPEFBs into bioethanol to meet future demand in the country. If implemented with combination of pre-treatment, the process efficiency of bioethanol production could be improved [65]. Thus, it is expected that an increased volume of bioethanol could be produced using the same amount of biomass. As stated previously, the review has shown that alkaline pre-treatment of OPEFBs (i.e. NaOH solution) offers superior performance in terms of bioethanol yield and has the lowest operational cost. Therefore, the alkaline pre-treatment is used in the proposed scenario for bioethanol production routes.

In the case of xylitol, Fig. 6b shows that physical pre-treatment of grinding was employed for reducing the particle size of OPEFBs. This was followed with hydrolysis using dilute H_2SO_4 (0.07%) with loading of 20% as previously explained in Mardawati et al. [124]. In this process, it is assumed that 100% of xylose content could be extracted from hemicellulose [124]; 97% of xylan could be converted to xylose and 2.9% of xylan is transformed into furfural [166]. Filtration would be carried out to separate hydrolysate from solid residues and impurities. During this process, it is proposed that cellulose, lignin, and remaining unconverted sugars (i.e. xylan, arabinose and glucose) be separated with a total calculated solid residue of 592.16 kg. Subsequent treatment would include the addition of activated carbon (3% of total hydrolysate volume) and filtration to remove any remaining lignin and some impurities (i.e. furfural, HMF, etc.) [167]; with total estimated amount of 148.61 kg. Evaporation process would then be employed to remove approximately 75% of water [168]. In this process, approximately of 3,750 L of water is evaporated and approximately 1,509.52 L hydrolysate is generated containing xylose, arabinose, and glucose [121]. Thus, the evaporation step in this proposed scenario could increase the concentration of xylose in the hydrolysate from 2% to 9.5%. Then, sterilization step is aimed to prevent any microbial contamination during fermentation, with assumption of no water or components loss. In the fermentation steps, *Debaryomyces hansenii* is added with solid loading of 3 g/L [74,105,111], the yeast is able to convert 87.89% of xylose to xylitol, 54.9% of arabinose to arabinitol, 97.22% or glucose into bioethanol, and biomass of 5.95% from xylose consumption. The purification process, composed of three main steps include (1) filtration, aimed to remove 100% of biomass, (2) evaporation, aimed to remove 100% of bioethanol and 75% of water, and (3) chromatography, aimed to remove 100% of unconverted sugars, 100% of arabinitol, and 10% of water. Approximately 126.34 kg of crude xylitol with 13.02% concentration is generated. The final process is crystallization, composed of three main steps include crystallization, centrifugation and drying. The crystallization process has an assumed efficiency of 77.6% and crystal's purity degree of 99.2 % [169], thus approximately 98.04 kg of xylitol crystal could be produced. Therefore, based on this mass balance, it is proposed that from 1000 kg of fresh OPEFBs, 98.04 kg (or 9.81%) of xylitol crystals could be generated. Thus, using the potential data of 45.86 Mt of OPEFBs/year, it is estimated that approximately 4.50 Mt of xylitol crystals could be produced in Indonesia per annum. Again, these findings demonstrate significant opportunities for valorizing OPEFBs into high-value chemicals such as xylitol.

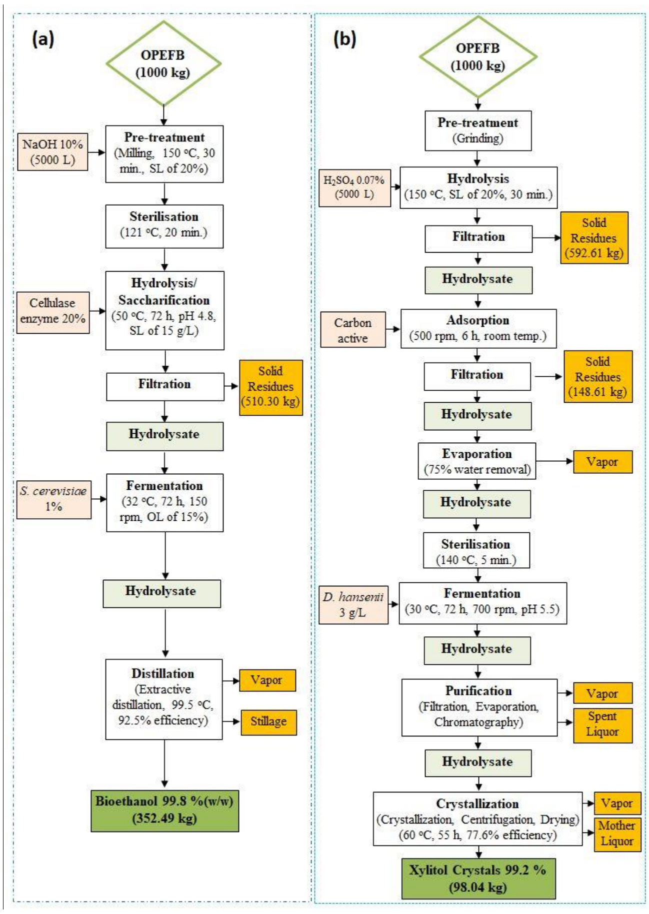

Fig. 6. Mass balance of mono-production of: (a) bioethanol and (b) xylitol (Scenario 1)

Table 10. A detailed mass balance for the proposed scenarios

Process Step	Input/Output	Total Volume/ Mass Scenario 1- Bioethanol	Scenario 1- Xylitol	Scenario 2 (Main product: xylitol, co-product: bioethanol, lignin)	Scenario 3 (Main product: bioethanol, co-product: xylitol, lignin)
Feedstock input	OPEFBs	**1000 kg dry weight:** 442.00 kg cellulose 204.00 kg lignin 19.00 kg other comp. 335.00 kg of hemicellulose: • 65.73 kg xylose • 80.43 kg xylan • 5.03 kg arabinose • 119.93 kg glucose • 63.88 other comp.			
(a) Bioethanol production steps					
Residues input*	OPEFBs residues	no		592.16 kg	no
Washing**	Clean water	no		2400.00 L water	no
	Dirty water	no		2400.00 L water	no
Pre-treatment	NaOH (10%)	**5000 L NaOH 10%:** 500 kg NaOH 4500 L water		**2960.81 L NaOH 10%:** 296.08 kg NaOH 2664.73 L water	**5000 L NaOH 10%:** 500 kg NaOH 4500 L water
Hydrolysis/ Saccharification	Solid Residue	**510.30 kg:** 106.08 kg cellulose 204.00 kg lignin 19.00 kg other comp. 181.22 kg hemicellulose: • 6.57 kg xylose • 80.43 xylan • 5.03 arabinose • 25.31 glucose • 63.88 other comp.		**186.28 kg[(a)]:** 106.08 kg cellulose 61.20 kg lignin 19.00 kg other comp.	**510.30 kg[(2)]:** 106.08 kg cellulose 204.00 kg lignin 19.00 kg other comp. 181.22 kg hemicellulose: • 6.57 kg xylose • 80.43 xylan • 5.03 arabinose • 25.31 glucose • 63.88 other comp.
	Hydrolysate	**5489.70 L:** 59.15 kg xylose 430.54 kg glucose 5000 L NaOH 10%		**3302.72 L:** 341.92 kg glucose 2960.807 L NaOH 10%	**5489.70 L:** 59.15 kg xylose 430.54 kg glucose 5000 L NaOH 10%
Fermentation	Fermented	**5489.70 L:**		**3302.72 L:**	**5489.70 L:**

	hydrolysate	26.24 kg xylose 107.64 kg glucose 352.49 kg bioethanol 3.34 kg biomass 5000 L water		66.16 kg glucose 256.44 kg bioethanol 19.32 kg biomass 2960.807 L water	26.24 kg xylose 107.64 kg glucose 352.49 kg bioethanol 3.34 kg biomass 5000 L water
Distillation	Water vapor	4998.23 L		2960.29 L water	4998.23 L
	Stillage	**137.21 kg:** 26.24 kg xylose 107.64 kg glucose 3.34 kg biomass		**85.48 kg:** 66.16 kg glucose 19.32 kg biomass	**137.21 kg:** 26.24 kg xylose 107.64 kg glucose 3.34 kg biomass
	Bioethanol (99.8%)	**352.49 kg bioethanol** 1.77 L water		**256.44 kg bioethanol** 0.51 L water	**352.49 kg bioethanol** 1.77 L water
(b) Xylitol production steps					
Residues input[***]	OPEFBs residues		no	no	510.30 kg
Hydrolysis	H_2SO_4 (0.07%)		**5000.00 L H_2SO_4 (0.07%):** 350.00 kg H_2SO_4 4650 L water	**5000.00 L H_2SO_4 (0.07%):** 350.00 kg H_2SO_4 4650 L water	**2551.51 L H_2SO_4 (0.07%):** 178.61 kg H_2SO_4 2372.90 L water
	Solid Residue		**592.16 kg:** 442.00 kg cellulose 61.2 kg lignin 19.00 kg other comp. 69.96 kg hemicellulose: • 0.08 kg xylan • 6.00 kg glucose • 63.89 kg other comp	**592.16 kg[(1)]:** 442.00 kg cellulose 61.2 kg lignin 19.00 kg other comp. 69.96 kg hemicellulose: • 0.08 kg xylan • 6.00 kg glucose • 63.89 kg other comp	**251.51 kg[(c)]:** 106.80 kg cellulose 61.2 kg lignin 19.00 kg other comp. 69.96 kg hemicellulose: • 0.08 kg xylan • 1.27 kg glucose • 63.89 kg other comp
	Hydrolysate		**5407.84 L:** 143.75 kg xylose 5.03 arabinose 110.46 kg glucose 142.80 kg lignin 2.33 kg furfural 3.49 kg HMF	**5407.84 L:** 143.75 kg xylose 5.03 arabinose 110.46 kg glucose 142.80 kg lignin 2.33 kg furfural 3.49 kg HMF	**2810.30 L:** 84.59 kg xylose 5.03 arabinose 23.31 kg glucose 142.80 kg lignin 2.33 kg furfural 0.73 kg HMF
Filtration	Solid Residue		**148.61 kg:** 142.80 kg lignin 2.33 kg furfural 3.48 kg HMF	**148.61 kg[(b)]:** 142.80 kg lignin 2.33 kg furfural 3.48 kg HMF	**145.87 kg[(d)]:** 142.80 kg lignin 2.33 kg furfural 0.73 kg HMF
	Hydrolysate		**5259.23 L:** 143.75 kg xylose	**5259.23 L:** 143.75 kg xylose	**2664.43 L:** 84.59 kg xylose

		5.03 kg arabinose 110.46 kg glucose 5000.00 L water	5.03 kg arabinose 110.46 kg glucose 5000.00 L water	5.03 kg arabinose 23.31 kg glucose 2551.51 L water
Evaporation	Water Vapor	3750.00 L water	3750.00 L water	1913.63 L water
	Hydrolysate	**1509.23 L:** 143.75 kg xylose 5.03 kg arabinose 110.46 kg glucose 1250.00 L water	**1509.23 L:** 143.75 kg xylose 5.03 kg arabinose 110.46 kg glucose 1250.00 L water	**750.80 L:** 84.59 kg xylose 5.03 kg arabinose 23.31 kg glucose 637.88 L water
Fermentation	Hydrolysate	**1509.23 L:** 9.29 kg xylose 2.27 kg arabinose 3.07 kg glucose 126.34 kg xylitol 2.76 kg arabinitol 107.39 kg bioethanol 8.12 kg biomass 1250.000 L water	**1509.23 L:** 9.29 kg xylose 2.27 kg arabinose 3.07 kg glucose 126.34 kg xylitol 2.76 kg arabinitol 107.39 kg bioethanol 8.12 kg biomass 1250.000 L water	**750.80 L:** 5.47 kg xylose 2.27 kg arabinose 0.65 kg glucose 74.35 kg xylitol 2.76 kg arabinitol 22.66 kg bioethanol 4.78 kg biomass 637.88 L water
Purification	Spent Liquor	**63.00 L:** 9.29 kg xylose 2.27 kg arabinose 3.07 kg glucose 2.76 kg arabinitol 8.12 kg biomass 37.50 L water	**63.00 L:** 9.29 kg xylose 2.27 kg arabinose 3.07 kg glucose 2.76 kg arabinitol 8.12 kg biomass 37.50 L water	**31.86 L:** 5.47 kg xylose 2.27 kg arabinose 0.65 kg glucose 2.76 kg arabinitol 4.78 kg biomass 15.95 L water
	Vapor	**982.38 L:** 875.00 L water 107.39 kg bioethanol	**982.38 L:** 875.00 L water 107.39 kg bioethanol	**509.44 L:** 478.41 L water 22.66 kg bioethanol
	Purified hydrolysate	**463.84 L:** 126.34 kg xylitol 337.50 L water	**463.84 L:** 126.34 kg xylitol 337.50 L water	**217.87 L:** 74.35 kg xylitol 143.52 L water
Crystallization	Water Vapor	0.42 L water	0.42 L water	0.111 L water
	Mother Liquor	**363.42 L:** 28.30 kg xylitol 335.11 L water	**363.42 L:** 28.30 kg xylitol 335.11 L water	**160.64 L:** 16.65 kg xylitol 143.99 L water
	Xylitol Crystal (99.2%)	**98.04 kg xylitol crystals** 8.27 kg water	**98.04 kg xylitol crystals** 8.27 kg water	**57.69 kg xylitol crystals** 4.62 L water
c. Solid residue recovery				

Solid Residue Recovery	**Lignin**	**204.00 kg lignin******	**204.00 kg lignin******	**204.00 kg lignin**	**204.00 kg lignin**

Note: Feedstock input composition are the same in all scenarios. *The composition of solid residue is the same as the composition of solid residue in (1); **Washing pre-treatment is applied on co-production scenario 2; *** The composition of solid residues is the same as the composition of solid residue in (2); **** Potential of the lignin amount to be recovered from the mono-production of bioethanol or xylitol; (a)(b) The amount of residues for lignin recovery in Scenario 2; (c)(d) The amount of residues for lignin recovery in Scenario 3.

For Scenario 2, as shown in Fig. 7, xylitol production is prioritized as the primary process. In this scenario, 9.81% of xylitol conversion efficiency from fresh OPEFBs is achieved. After the hydrolysis and filtration process, it is calculated that 592.16 kg of solid residues, rich in cellulose and remaining glucose, are produced. These components can be further valorized into bioethanol. Using the same assumption explained previously, approximately 256.44 kg of bioethanol could be generated from conversion of cellulose to glucose and glucose to bioethanol (or 43.31% of conversion efficiency). Therefore, from 45.86 Mt of OPEFBs/year, it is projected that 4.50 Mt of xylitol, 11.76 Mt of bioethanol, and 9.36 Mt of lignin could be co-produced.

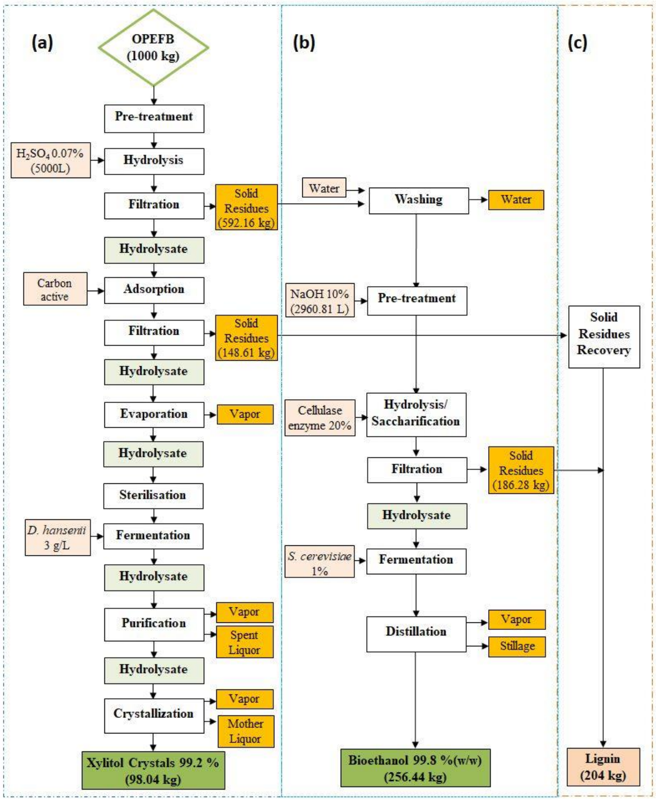

Fig. 7. Mass balance of co-production of xylitol and bioethanol (Scenario 2)

Fig. 8 shows a mass balance from Scenario 3, where the co-production process pathway emphasizes bioethanol as the main product. It can be seen that, based on 1000 kg of fresh OPEFBs, an estimated 352.49 kg of bioethanol and approximately 510.30 kg of solid residues (rich in xylan, xylose and cellulose) could be produced. By adding acid pre-treatment into the remaining solids, conversion of xylan into xylose is also highly achievable. Thus, the xylose component remaining in the hydrolysate can be further fermented by *Debaryomyces hansenii* into xylitol. The figure shows that from 510.30 kg of solid residues can generate 57.69 kg xylitol crystals, accounted for 11.31% yields. Therefore, based on OPEFBs production of 45.86 Mt/year, it is estimated that there is a theoretical potential production of 16.17 Mt of bioethanol, 2.58 Mt of xylitol, and 9.36 Mt of lignin.

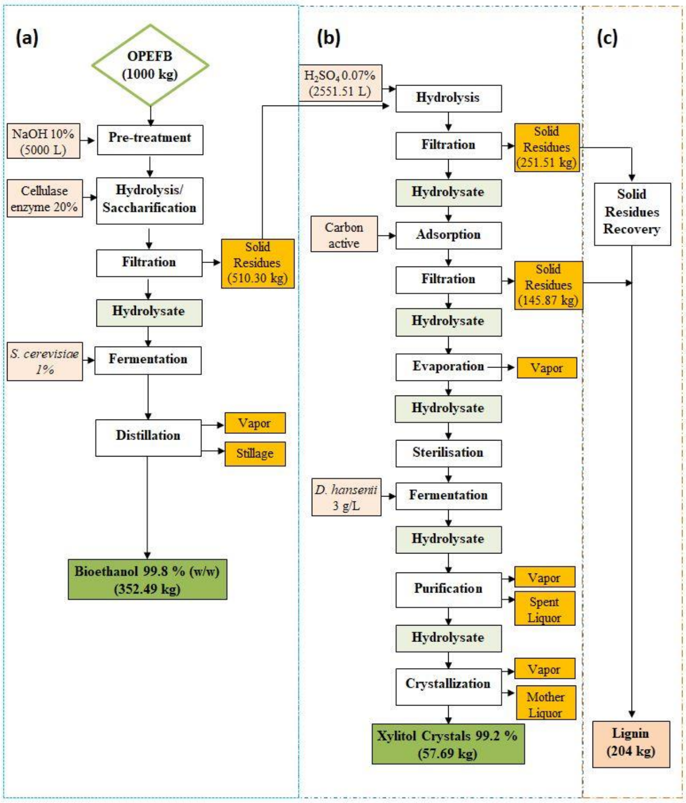

Fig. 8. Mass balance of co-production of bioethanol and xylitol (Scenario 3)

Table 11. Summary of estimated potential production (Mt/year) based on 3 scenarios

Type of scenario	Primary Process Stream	Estimated Potential Production (Mt/year)		
		Bioethanol	Xylitol	Lignin
Scenario 1 Mono-production	Bioethanol	17.12	/	9.36
	Xylitol	/	4.50	9.36
Scenario 2 Co-production	Xylitol	4.50	11.76	9.36
Scenario 3 Co-Production	Bioethanol	16.17	2.58	9.36

It is that, while scenario 1 offers the greatest potential for bioethanol production, Scenario's 2 and 3 offer additional benefits in terms of complete resource recovery from raw OPEFBs and in doing so reduce streams that may have contributed to environmental pollution [67]. There is limited production of both xylitol and bioethanol in Indonesia. Co-production of these via a biorefinery approach could improve commercial viability of bioethanol production and help to address increased future demand, reduce reliance on imported products and meet national targets for sustainable energy production.

5.2.3. Economic projections

An economic analysis was carried out to investigate the commercial viability of the three scenarios. The assumptions used in the economic analysis are shown in Table 12. The total raw material of fresh OPEFBs is assumed to be 126 kt/year (or 40 tons OPEFBs/h) based on Abdurachman and Gozan [170], where a POM treating about 555-575 tons FFB/h, generated 108.8 tons OPEFBs/h. The plant area is assumed to cover 2 Ha land and be constructed in close proximity to the POM to reduce the cost of transporting biomass. It is also assumed that the POMs have power generation, where the electricity needs are supplied at cost of 0.038 US$/kWh [16]. The production capacity of bioethanol, xylitol and lignin for all scenarios is calculated based on the mass balances as explained in previous section.

Table 12. Project parameters and prices used in the economic analysis

No.	Description	Unit	Value			
			Scenario 1-Xylitol	Scenario 1-Bioethanol	Scenario 2	Scenario 3
1.	Input raw material (OPEFBs)[a]	kt/year	126	126	126	126
2.	Production capacity					
	Bioethanol	kL/year	0	46,145	32,302	46,145
	Xylitol	kt/year	14.010	0	14.010	7.716
	Lignin	kts/year	25.704	25.704	25.704	25.704
3.	Price of product					
	Bioethanol	US$/L	0.77[b]			
	Xylitol	US$/kg	3.0[c]			
	Lignin	US$/kg	1.0[c]			
4.	Project lifetime	year	15[d]			
5.	Composition of direct fixed cost[d]					
	Total plant direct cost (TPDC)					
	- Major equipment cost (MEC)					
	- Installation cost		30% of MEC			
	- Process piping cost		20% of MEC			
	- Instrumentation cost		20% of MEC			
	- Insulation cost		3% of MEC			
	- Auxiliary facilities cost		20% of MEC			
	Total plant indirect cost (TPIC)					
	- Engineering part cost		10% of TPDC			
	- Constructions cost		10% TPDC			
	Contractor's Fee and Contingency (CFC)					
	- Constructions fee		5% of TPC (TPC=TPDC+TPIC)			
	- Contingency		5% of TPC			
6.	Land[e]	Ha	2			
7.	Laboratory charges[e]	US$	10% of labor cost			
8.	Income tax[a]	%	40			
9.	Water price[e]	US$/m^3	0.02			
10	Electricity price[e]	US$/kWh	0.038			
11	Utilities steam[e]	US$/ton	5.3			
12.	Yeast price[f] (*S. cerevisiae*)	US$/kg	1.72			
13.	Yeast price[f] (*D. hanseii*)	US$/kg	1.95			
14.	OPEFBs price[f]	US$/kg	0.01			
15.	NaOH price[f]	US$/kg	0.43			
16.	Electricity needs[f]	kWh/kg	7.35			
17.	Enzyme price[g]	US$/kg	0.077			
18.	H_2SO_4[c]	US$/kg	0.0094			
19.	Operating labour salary[f]	US$/h	0.9			
20.	Working hour[f]	hours/day	8			
21.	Working days[f]	days/year	300			
22.	Staff	people	75			
23	Operating labour	people	60	60	70	70

Notes: [a] Abdurachman and Gozan [170]; [b] Maryana et al. [171]; [c]Medina et al. [38]; [d] Hafid et al. [172]; [e] MEMR [16]; [f] Harahap et al. [173]; [g] Do and Lim [164]; 1 US$ is equal to IDR 14,500 as per exchange rate on 13 July 2021

The output of the economic analysis is shown in Table 13. For all scenarios, calculations are based on commercial scale applications described in peer reviewed literature. The total investment cost in this proposed project is based on studies from MEMR [16]; Vaskan et al. [37]; Medina et al. [38]; Hafid et al. [172]; and

Harahap et al. [173]. The capital investment costs comprises of total plant cost (TPC), direct fixed cost (DFC), working capital, license, building and land, power plant and waste management utilities. The TPC is calculated as addition of total plant direct cost (TPDC) and total plant indirect cost (TPIC), while DFC is calculated by adding TPC with contractor's fee and contingency (CFC). The composition of TPDC, TPIC and CFC, in details can be seen in Table 11, with the respective percentage assumed for each cost. The major equipment cost (MEC) relates to major equipment such as fermentation tank, distillation column, sterilization tank, pumps, storage tank, heater, condenser, filter and etc. In this proposed scenario for xylitol production, the MEC is re-calculated proportionally based on Medina et al. [38] with a production capacity of 200 kt OPEFBs/year. While, for the bioethanol process stream, the values for MEC is recalculated from techno-economy study by Abdurachman and Gozan [170], which has capacity of 126 kt OPEFBs treated for bioethanol production in Indonesia. For Scenario 2 and 3, the MEC is proportionally calculated as the sum of on the initial production capacity of 126 kt OPEFBs/year, plus the production capacity of remaining solid residues.

Total capital investment for mono-production of xylitol and bioethanol (Scenario 1) is predicted at 72.688 million US$ and 60.583 million US$, respectively. Retrofit of an additional process stream for co-production of bioethanol (where xylitol is the primary process stream) would incur an additional capital investment cost of 90.950 million US$. Similarly retrofit of an additional process stream for co-production of xylitol (where bioethanol is the primary process stream) would incur an additional capital investment cost of 82.222 million US$.

The annual operating and maintenance cost in this proposed project is estimated at 32.187 million US$ and 28.828 million US$ for mono-production of xylitol and bioethanol. The cost is projected to increase to 35.119 million US$ (Scenario 2) and 32.791 million US$ (Scenario 3), to account for the additional conversion of the solid residues. The operating and maintenance cost is calculated from addition of variable cost (VC) and fixed cost (FC). The VC structure is raw material, utilities, consumables, labour-depended, laboratory charges, variable marketing cost, variable maintenance cost, and other VC. FC structure include equipment depreciation, bank interest, fixed labour cost, land and building tax, insurance, maintenance, plant overhead, marketing and distribution and administration costs. In this project, it is assumed that the plant can process 40 tons of OPEFBs per batch [170,172]. Based on the data used in this study, the cost of production for bioethanol and xylitol is estimated to be 0.625 US$/L and 2.297 US$/L.

The total income is based on the market value of the main products at a price of 0.79 US$/L bioethanol [171] and 3 US$/kg xylitol [38]. The calculation also includes sale of lignin as the solids residues generating from all scenarios, at a price of 1.0 US$/kg [38]. The economic analysis indicates that all scenarios have a positive NPV (at 10% interest). For mono-production (Scenario 1) it can be seen that producing xylitol provides a higher income compared to that of bioethanol. However, when the existing xylitol plant, is expanded to incorporate co-production of bioethanol and lignin, as shown in Scenario 2, a moderate reduction in the after-tax IRR, ROI, Net B/C, and PP values can be seen. If an existing bioethanol plant is upgraded to process the solid residues into xylitol and lignin, this could improve commercial viability. The findings confirmed that OPEFBs valorization into bioethanol and xylitol are economically feasible, as the solid residues can be valorized for alternative fuels or high-value added chemical. Scenario 3 may provide attractive opportunities for existing conventional POMs or OPEFBs-based bioethanol plants in Indonesia. Currently, there is limited information on existing xylitol production plants in Indonesia, thus Scenario 1-Xylitol or Scenario 2, warrant further investigation as potential opportunities for the country.

Table 13. Overall economic indicators for all scenarios of bioethanol and xylitol production from OPEFBs

Description	Unit	Values			
		Scenario 1-Xylitol	Scenario 1-Bioethanol	Scenario 2	Scenario 3
Total Capital Investment	million US$	72.688	60.213	90.950	82.222
Total Production Cost	million US$	32.187	28.828	35.119	32.791
Total Income	million US$	67.734	62.302	93.,353	85.449
Gross Profit	million US$	35.547	33.474	58.,234	52.658
Tax (40%)	million US$	14.219	13.390	23.294	21. 063
Net Profit after tax	million US$	21.328	20.085	34.940	31.595
Net Present Value (NPV) (at 10% interest)	million US$	29.957	32.178	98.609	91.678
Internal Rate of Return (IRR) after tax	%	12.20	12.89	17.27	18.22
Return of Investment (ROI)	%	7.21	11.81	20.72	22.77
Net B/C		1.24	1.31	1.49	1.48
Payback Periods (PP)	years	4.93	4.43	3.61	3.64

Study by Abdurachman and Gozan [170] reported that production of bioethanol from OPEFBs at scale of 40 tons/h (or 126 kt/year) with SSF and adsorption technology in Indonesia is projected to have a PP of 4.92 years, ROI of 20.32%, IRR of 14.77%, and profit margin of 12.93%, respectively. A report on bioenergy guidelines in Indonesia from MEMR [16] stated that the investment costs for a bioethanol conversion plant from cassava at capacity of 13,261 kL would give IRR of 20.42%, ROI of 23.9% and PP of 4.3 years. Therefore, the economic evaluation provided here demonstrates similar PP in Scenario 1. However, it can be seen from Table 12 that this is reduced to 3.61 and 3.64 years in Scenario 2 and 3, respectively. This is supported by Vaskan et al. [174], who suggest that valorizing OPEFBs into 2G bioethanol can be economically improved by integrating with the production of high-value added chemicals (i.e. C5 syrup) or biodiesel within the factory. Their study found that the income obtained from selling multiple products of bioethanol and C5 syrup gave higher profits than that of bioethanol as a main product. Medina et al. [38], also demonstrated that biorefining ethanol, xylitol and lignin from OPEFBs in Brazil provided better economy profit compared to the production of bioethanol alone.

6. Challenges for scaling-up and commercialization

Despite the clear opportunities presented, there remains a number of challenges in converting lignocellulosic biomass into bioethanol. These broadly fall into technical, supply chain, economic, and policy/ regulatory challenges.

6.1. Technical challenges

Technical challenges include the reported low efficacy of fermentation of lignocellulosic biomass (mainly due to high lignin content and the structure of crystalline polymer) [128,175]. Studies have reported various strategies to address this and enhance fermentation efficacy, for example applying detoxification process or removal of fermentation inhibitors (i.e. furfural and HMF) [176,177]; optimizing particle size or combining pre-treatments prior fermentation [178–180]; using high-tolerance inhibitors or effective genetic modified microbial strains [179,181]; or using thermophilic cellulolytic anaerobic bacteria as it can stand to high temperature for better fermentation process [182]. Several studies have highlighted the challenges with xylitol production, predominantly the identification and optimization of microorganism with superior performance (i.e. high yield, high productivity). This may positively impact on reducing energy requirements for conversion and purification [183]. A lack of research and development surrounding pre-treatment optimization and co-production of bioethanol with other high value products is also commonly cited as a barrier to commercialization [16,184]. The availability of scaled technologies also hinders wider implementation [110]. Current methods can only extract a small fraction of xylitol, therefore, better procedures or methods for improving the efficacy of purification and crystallization of xylitol are required [70,119]. This review emphasized that the pre-treatment and the conversion technology selection are challenges for scale up and commercialization of lignocellulosic biomass to bioethanol and xylitol, either in single or integrated co-production mode [183]. Land availability for new bioethanol plants and infrastructure limitations also need to be addressed within the country [16].

6.2. Supply chain challenges

There are inherent challenges surrounding sustainability supply chain integration and the mobilization of biomass within the country (especially given that Indonesia is an archipelagic country), which include the geographic distribution nature of biomass sources, availability of each biomass type, and biomass properties [16,70,119,183,185]. In Indonesia, OPEFBs is mainly concentrated in Sumatra and Kalimantan Island [16]. This would be an issue if production was located at distance from supply rather than within existing palm oil facilities. This would result in additional costs and emissions from transportation [186,187]. To ensure sustainability, production of bioethanol/xylitol is recommended in-situ or within close proximity to oil palm plants. Several studies found that biomass collection and storage could be challenging for commercial scale biofuel production leading to increase environmental impacts (i.e. carbon emissions) [182,188]. Further work is required to map these bioresources to ensure future provision is geographically optimal and can be managed in a sustainable way.

6.3. Economic challenges

Economic challenges include high initial capital investment required at project implementation stage [16]. The review highlighted that deployment of a new bioethanol or xylitol plant requires various investment cost including the purchase of key processing equipment, legal licenses and administration, and infrastructure costs (i.e. land, building, working capital, etc.). Scalability is challenge and a study by Sharma et al. [189] and Lennartsson et al. [190] reported that demonstration scale bioethanol plants have yet to prove economic feasibility of the process. They recommend to implement co-production of bioethanol with other high-value added products, valorized from the residual solids waste. Such measures could offer better economic and environmental profits. Therefore, in this study, the proposed scenario of expanding process streams from the residual solids waste into bioethanol or xylitol may provide an important step towards the development of a sustainable bioeconomy.

6.4. Policy and regulatory challenges

The Indonesian Government has, through Regulation of MEMR No. 12 (2015) set out policy for the mandatory use of biodiesel and bioethanol blending. This roadmap provides guidelines for the minimum use of bioethanol across several sectors, as shown in Table 14. Further legislative support for bioethanol is provided via policies of Directorate General of NREEC Number 722 K/10/ DJE/2013 which outlines biofuel standards and quality (specification) based on the Indonesian National Standard (SNI 7390:2012) [16], as can be seen in Table 15 for bioethanol specification. The legislation provides guidelines on the maximum bioethanol concentration (of 10%) allowed in the gasoline mixture. With Regulation MEMR No. 25 (2013), the Indonesian government is committed to further enforce and supervise the biofuels utilization in practice, through cross-sectoral coordination with Directorate General of NREEC, the Directorate General of Oil and Gas, Directorate General of Electricity, Directorate General of Mineral and Coal, and related ministries/agencies. With this regulation, related parties and stakeholders are required to maximize the use of biofuels produced in Indonesia for transportation and industrial activities. Any businesses who do not adhere to the compulsory use of biofuels legislation could receive sanctions including business license revocation. The above legislations further promotes the use of bioethanol as an alternative fuel to be marketed in Indonesia.

Table 14. Bioethanol (minimum) use based on Government Regulation of MEMR No. 12 Year 2015 [9]

Sectors	April 2015	January 2020	January 2025	Notes
Households	-	-	-	Not specified
Micro Business, Marine Fisheries, Farming, Transportation and Public Service Transport (PST)	1 %	5%	10 %	Against the total requirement
Transport non PST	2%	10%	20%	
Industry and commercial	2%	10%	20%	
Power Plants	-	-	-	

Table 15. Standard specification of bioethanol according to SNI 7390:2012 [191]

Characteristics	Unit	Specification	
		Min.	Max.
Ethanol	% - volume	99.5	-
Methanol	% - volume	-	0.5
Water	% - volume	-	0.7
Denatonium benzoate	mg/L	4	10
Cooper (Cu)	mg/kg	-	0.1
Acid as acetic acid	mg/L	-	30
Visual appearance		Clear and light, no deposits and dirt	
Chloride ions (Cl^-)	mg/L	-	20
Sulfur (S)	mg/L	-	50
Washed Gum	mg/100 mL	-	5

Despite a clear policy framework and ambitious targets implementation at regional level and translation of policy into adoption and deployment of bioenergy production facilities is lacking. For instance, there remains a lack of financial initiatives supporting biomass to bioethanol energy plants [16]; as well as a lack of subsidies for gasoline-operated vehicles and motorcycles for the use of blended bioethanol-gasoline [10]. The feed-in-tariff policies for bioenergy based power plants in Indonesia is currently available for electricity production from biomass, biogas and MSW [192]. Fossil fuels, however are heavily subsidized which prevents wider adoption of biofuels and bioenergy technologies and processes. Based on Government Regulation of MEMR No. 18 (2013) [193] and Presidential Regulation No. 191 (2014) [194], the government has established a retail selling price for subsidized fossil fuels and a list of targeted customers. According to Dutu [4], as fossils fuels remain a key export income for Indonesia, the policies around providing subsidized fossil fuels remain a priority. He added that more than 20% of government spending was directed towards fuel subsidies targeting affordable energy for the poor and to enhance household purchasing power. However, this policy is not well implemented as only <1% of the subsidy benefits went to the poorest and >40% went to the richest. Chattopadhyay and Jha [195] stated that policies on energy subsidies in developing countries include Indonesia has limited the ability of the state-owned utilities to expand their energy sufficient capacity. According to Singh and Setiawan [196], the bioethanol program in Indonesia has been stopped since 2010 due to ongoing disagreements between the Government (MEMR) and the bioethanol producers over the market price index. There is little information available regarding regulatory support for production of high value products such as xylitol.

7. Conclusion

This review has identified the significant opportunities for OPEFBs valorization in Indonesia. There is a growing demand for bioethanol (and bio-based products such as xylitol) which cannot currently be met through local production. Increasing national production capacity is imperative if the country is to meet its targets for renewable energy production and reduce its reliance on fossil derived fuels. This paper presents a number of novel process configurations that would improve the commercial viability of bioethanol production through co-production of high value products such as xylitol. In terms of conversion pathways, it was determined that pre-treatment is critical to overcome challenges of high lignin and fiber content of OPEFBs. The most appropriate pre-treatment was identified as a combination of physical pre-treatment with dilute alkaline for bioethanol or with dilute acid for xylitol process stream. The challenges for this approach are the requirement for corrosion-resistant equipment, safe disposal of waste chemicals, and sustainable wastewater treatment.

Various scenarios were explored which could offer opportunities for existing production facilities (including palm oil mills), where retrofit of additional process streams could allow for co-production leading to additional income generation, waste reduction and resource recovery. Alternatively, given the limited existing production capacity, new industries could emerge to meet increasing demand. Although the economic assessment only provides a crude estimation based on optimal process efficiencies, it can be argued that all scenarios are economically attractive. Undoubtedly, greater financial incentives (and a reduction in fossil subsidies) would further improve the economic viability of this proposition. Further work is required to address the challenges of scalability and process performance as well as to better understand the supply chain and logistical challenges which arise from mapping and managing bioresources such OPEFBs in an archipelagic country such as Indonesia.

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Figure captions

Fig. 1. Distribution of potential palm oil waste-based power plants as in 2021 (With permission from Directorate General of NREEC, MEMR and ExploRE Project, GIZ [89]). POMs: Palm Oil Mills, FFB: Fresh Fruit Bunches

Fig. 2. Stages of the conversion process of OPEFB into bioethanol (Adapted from Derman et al. [34]; Hendriks and Zeeman [64]; and de Paula et al. [15]). SHF: Separated hydrolysis and fermentation, SSF: Simultaneous saccharification and fermentation, PSSF: Pre-hydrolysis simultaneous saccharification and fermentation, Q-SSF: Quasi-simultaneous saccharification and fermentation, SScF: Simultaneous saccharification and co-fermentation

Fig. 3. Flow chart of xylitol production – chemical, biological and thermochemical processes (Adapted from Rao et al. [70]; Irmak et al. [117]; Rafiqul and Mimi Sakinah [113]; Martínez et al. [118])

Fig. 4. Trend and projection of (a) bioethanol demand and (b) supply in Indonesia (With permission from Secretariat General of the National Energy Council, MEMR [1]). BaU: Business as Usual, PB: Sustainable Development/*Pembangunan Berkelanjutan*, RK: Low Carbon/*Rendah Karbon*

Fig. 5. Scenarios of OPEFBs valorization into bioethanol and xylitol production

Fig. 6. Mass balance of mono-production of: (a) bioethanol and (b) xylitol (Scenario 1)

Fig. 7. Mass balance of co-production of xylitol and bioethanol (Scenario 2)

Fig. 8. Mass balance of co-production of bioethanol and xylitol (Scenario 3)